FINAL SCIENTIFIC REPORT

on

Contract AFOSR 81-0093

"Investigation of RF Emissions From
Two Beams Interacting with an
Electric Field Dominated Plasma"

March 15, 1981 To March 14, 1986

J. Reece Roth
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This final scientific report summarizes a five year program of experimental research on a steady state, electric field dominated, classical Penning discharge at the University of Tennessee's Plasma Science Laboratory. This research effort spanned the five year period from March 15, 1981 to March 14, 1986. It required a total of 1.25 man-years of the Principal Investigator's time, 4.5 man-years of UTK Graduate Research Assistant time, 0.4 man-years of faculty time other than that of the Principal Investigator, and required $325,060, for expenses.

The objectives of this research program were to study RF emissions and RF interactions with a steady-state, electric field dominated plasma which exhibited instabilities associated with two interpenetrating electron beams. Among the scientific results of this contract are the observation and identification of the geometric mean emission frequency, a two-interpenetrating beam plasma instability jointly discovered by the Principal

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Investigator and Prof. Igor Alexeff. The RF emissions associated with the geometric mean emission frequency and its harmonics could produce, under some conditions, a virtually flat white noise spectrum from below 0.5 megahertz to frequencies above 1.2 GHz. Quantitative investigations during the latter part of this contract showed that the efficiency of converting the dc electrical power input of the classical Penning discharge into broadband RF radiation was no more than 0.1 or 1.0%.

High levels of electrostatic turbulence, anomalous electrical resistivity, and very strong axial and radial electric fields were observed in this steady state, classical Penning discharge. RMS levels of electrostatic plasma turbulence were sometimes in excess of several volts; axial and radial electric fields in excess of several hundred volts per centimeter were measured in this discharge. These phenomena provide both a mechanism for creating high energy density plasmas in the steady-state, and a physical explanation for the implied anomalous electrical resistivity. Our studies of heating in turbulent plasmas have led us to investigate collisional magnetic pumping. We now believe that collisional magnetic pumping may be highly effective in turbulent, electric field dominated plasmas and that the heating rate might be many hundreds of times faster than assumed in early work done in the 1950's. In addition to these scientific results, this contract has also supported three graduate students who have obtained their Master's degree in Electrical Engineering, one student who is shortly to obtain his Ph.D. in Electrical Engineering, and a number of additional students who will complete their degree program after their employment on this contract. This contract was used as a vehicle for a very successful pilot program for undergraduate research assistants who worked in the Plasma Lab during the Summer of 1985, and contributed their efforts to our research program. This contract also supported a computational physics effort off campus, during its final year.

Final Scientific Report

on

Investigation of RF Emissions from Two Beams Interacting with an Electric Field Dominated Plasma

for the period
March 15, 1981 to March 14, 1986

Submitted to

THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

by

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UTK Plasma Science Laboratory
Report No. 86-1

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Principal Investigator

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EXECUTIVE SUMMARY

Background Information

This document describes a recently-completed five-year program of research at the University of Tennessee's Plasma Science Laboratory, which is located on the Knoxville campus, and affiliated with the Electrical Engineering Department. Our Laboratory specializes in the experimental investigation of interactions between RF radiation and plasmas, and on research in electric field dominated, steady-state plasmas. These plasmas exhibit several unique characteristics: very high levels of plasma turbulence; broad-band radio frequency emission; ion kinetic temperatures up to several kilovolts; ion kinetic temperatures much higher than that of the electron population; and strong axial and radial electric fields, measured values of which have been in excess of several hundred volts per centimeter along the magnetic field. The presence of strong electric fields in the plasma allows work from external sources to be done on the plasma, thus affecting its confinement, heating, and transport properties. Such electric field dominated plasmas can achieve high energy densities, and are of potential utility in such applications as lasers, pulsed broad-band radio frequency emitters, high power sub-millimeter microwave emission, communications, and directed energy weapons.

The level of effort of this contract during its five year duration is summarized on Table 1. This contract covered a five year period in one year increments, which extended from March 15 through March 14 of the following year. The contract supported the Principal Investigator for 1/4 time during

TABLE 1

MANPOWER ALLOCATIONS, BUDGETS, AND DOCUMENTATION

Year	Period	P.I. Time Man-Years/ Year	GRA Time Man-Years/ Year	Yearly Budgets,	Interim Scientific Report UTK Number	Proposal UTK Report Number
1	3/15/81 - 3/14/82	0.25	0.5	$38,930	PSL 82-2	PSL 80-1
2	3/15/82 - 3/14/83	0.25	1.0	$57,348	PSL 83-1	PSL 81-1
3	3/15/83 - 3/14/84	0.25	1.0	$64,168	PSL 84-3	PSL 82-4
4	3/15/84 - 3/14/85	0.25	1.0	$68,007	PSL 85-3	PSL 83-3
5	3/25/85 - 3/14/86	0.25	1.0	$96,607	This report	PSL 84-4, 85-1
TOTALS		1.25	4.5	$325,060		

the entire duration of the contract. It also supported one graduate research assistant during the first year of the contract, and two graduate assistants during the subsequent four years. The total budget for the contract over the five year period was $325,060, an amount which supported the 16 archival and conference presentations listed in Appendix C, and supported in whole or in part four graduate experimental theses at the UTK Plasma Science Laboratory. The activities of each year have been documented in detailed Interim Scientific Reports, with the UTK report number listed in Table 1, which were submitted to AFOSR, and are available in its archives. In addition, each of the five years required a proposal, which is documented in the UTK reports listed in the last column of Table 1.

Objectives of Research

The initial objective of this contract was to experimentally identify and confirm the existence of the geometric mean interpenetrating beam plasma instability in a classical Penning discharge, and to further explore the radio frequency emissions from this steady state, electric field dominated plasma. As the contract progressed beyond its first year, exploratory research with the diagnostic instruments available in the UTK Plasma Science Laboratory revealed additional interesting phenomena, which were incorporated among the objectives for the final three years of the research program.

The objectives of the research during the initial two years were to set up, with AFOSR support, a classical Penning discharge in the UTK Plasma

Science Laboratory, and then to identify and confirm the existence of the geometric mean plasma oscillation in the steady-state, electric field dominated plasma. The geometric mean emission frequency was discovered jointly by Professors J. Reece Roth and Igor Alexeff of the UTK Plasma Science Laboratory. These objectives were met by the end of the second year of the contract. Exploratory research during the second year of the contract revealed broadband, white-noise-like RF emission from the classical Penning discharge, of a kind that might be useful for jamming or EMI simulation. Strong axial and radial electric fields also were observed, as well as high levels of plasma turbulence.

It became our objective during the third and fourth years of the contract to study the strength and nature of the broadband emissions from the classical Penning discharge; to study the interactions of microwave radiation with the classical Penning discharge plasma; to study the drift waves and turbulence observed in the plasma using time series analysis techniques; and to understand the anomalously high electrical resistivity observed in this plasma. Finally, during the last year of the contract, theoretical insights into the plasma heating process, which originated outside the scope of this contract, were followed up by Mr. Mounir Laroussi in a theoretical analysis which indicates that collisional magnetic pumping can be up to several hundred times more effective than previously believed possible if one goes about it in the right way. A theoretical study of this "first-order collisional magnetic pumping" then became an objective for the final year of the contract, and was the subject of a recent theoretical publication.

Five-Year Technical Results

During the first year of this contract a steady state, electric field dominated classical Penning discharge plasma facility was designed, assembled, and put into operation. This facility, which remains in active use in the UTK Plasma Science Laboratory, consists of a steady-state classical Penning discharge operating in a water cooled magnet system which is capable of 0.4 tesla. The high voltage power supply, magnet system, cooling water, and vacuum system were assembled; and the first plasma achieved near the end of the first year of this contract. During that first year, diagnostic systems were put into operation which included spectrum analyzers to examine RF emissions up to 28 GHz, and a retarding potential energy analyzer. At the end of the first year, the plasma was capable of operating for hours at a time and was observed to exhibit a broad-band RF white-noise spectrum over frequencies from 0.5 megaHertz to 1.0 GHz. The discharge was also observed to produce ions with characteristic energies, along the magnetic field lines, of several hundred electron volts, and the discharge also exhibited evidence of strong electric fields, up to severeal hundred volts per centimeter, along the magnetic field in the plasma.

During the second year of this contract, additional diagnostic systems were placed into service, including a high voltage Langmuir probing system for axial profile measurements, and an active RF diagnostic system to measure plasma number density by observing the absorbtion of RF power at the electron plasma frequency. Phenomena investigated during this contract

period included RF emission at frequencies over the band from 0.5 MHz to 2 GHz; ion energies and ion energy distribution functions; axial electrostatic potential profiles; and a rich variety of nonlinear mode coupling phenomena among the various RF, near-field emissions from the plasma.

During the third year of this contract, additional diagnostic systems were placed into service, which included specially made, broad-band antennae for the measurement of absolute RF emission levels over frequencies from approximately 50 MHz to 1200 MHz; a 32 GHz microwave scattering apparatus for the detection and study of plasma density fluctuations; and a two channel, analog-to-digital data handling system capable of measuring fluctuating phenomena up to 10 MHz, with associated software capable of obtaining auto and cross power spectra, phase spectra, and coherency spectra at frequencies up to 10 MHz. The two-channel data handling system was used to compare the density fluctuation signals obtained from the microwave scattering experiment with the fluctuating electrostatic potentials from a Langmuir probe on the plasma edge. This data handling system was also used to compare the fluctuating electrostatic signals from two capacitive probes located at different azimuthal or axial positions with respect to the plasma. The plasma fluctuation measurements made with the microwave scattering apparatus and the capacitive probes indicate a low frequency disturbance, in the range of 10 to 50 KHz in the plasma, the frequency of which is directly proportional to the magnetic field strength. This frequency is far too low to be associated with the ion or electron cyclotron frequency, or the Alfven velocity in this plasma.

During the fourth year of this contract, more detailed investigations of the broad-band RF emissions, from below 1 MHz to more than two GHz, were conducted. These emissions were found to be incoherent; the emitted radiation intensity was proportional to the electron number density and not to its square. A calibrated, broadband antenna was developed which had a flat frequency response from approximately 100 MHz to 1.2 GHz. Measurements made with this antenna showed that the efficiency of generating the RF emissions was only about 0.1%, and decreased with increasing plasma number density. During this fourth year, microwave scattering measurements made in connection with a master's thesis revealed very high amplitude number density fluctuations within the plasma, with the fluctuations reaching 6% of the rms number density. An important density fluctuation phenomena revealed during these measurements was a spoke, which rotated about the axis of the discharge with a frequency of several 10's of KHz.

During this fourth year, a theoretical program was undertaken to look in more detail at the theory of interpenetrating electron beams, which describes the geometric mean emission frequency and is related to the high levels of electrostatic turbulence in the plasma. This theory was extended by Prof. Igor Alexeff and the Principal Investigator to include a cold background plasma in the region in which the two interpenetrating beams interact. A second line of theoretical investigation was initiated during this fourth year by the Principal Investigator and the Senior AFOSR Graduate Research Assistant supported by this contract. The GRA repeated and extended some old work on collisional and transit time magnetic pumping, to include recent

insights about this heating method which imply that it might be made far more efficient and effective than the old theory suggested.

Finally, in the final year of this five year contract, the theoretical investigations of collisional magnetic pumping paid off with the very interesting prediction that collisional magnetic pumping might be made several hundred times more effective than previously believed possible, by a rather simple modification of the collisional magnetic pumping process. The old theory predicted second order plasma heating, proportional to the square of the ratio of the perturbed magnetic field to the background, steady-state magnetic field. The new theory shows that, if the perturbed field is at all times greater than the background, constant magnetic field, the plasma heating rate is linearly proportional to this pertubation parameter.

The experimental program during this final year of research also produced some very interesting and significant results. An active microwave plasma diagnostic procedure, which utilized the Hewlett Packard microwave network analyzer bought with the AFOSR URIP funding, and which was developed under our ONR contract, was applied to the plasma in the classical Penning discharge. This diagnostic procedure allowed us, for the first time, to measure the effective collision frequency in the classical Penning discharge plasma. It was found that, at low magnetic fields, below approximately 0.25 Tesla, the effective collision frequency in the classical Penning discharge plasma was approximately 0.5 MHz, a value consistent with electron-neutral impact collisions in the plasma containment volume. At higher magnetic fields, however, the effective collision frequency increased dramatically, to

values approaching 20 MHz, as the magnetic induction approached values of 0.4 Tesla. This dramatic increase in the effective collision frequency is associated with increased levels of turbulence in the plasma, which scattered the electrons more effectively than electron-neutral collisions.

Results of Other Contract Programs

This contract also supported other activities in aid of our experimental and theoretical research program. A major initiative in the fourth and fifth year of this contract was a collaborative arrangement in computational physics with Dr. Robert J. Barker of AFOSR. Our contract was used as a vehicle to enable Dr. Barker to purchase the computer hardware and software required for this collaborative activity.

Another activity was the purchase of equipment, including low frequency and high frequency (microwave) network analyzers, with $233,745 of fiscal year 1985 funds which UTK was given by AFOSR under the Department of Defense-University Research Instrumentation Program (URIP). Another activity, in the second and fourth year of this contract, was participation by the Principal Investigator in the International Conferences on Plasma Physics held during the early summers of 1982 and 1984, the first in Goteborg, Sweden, and the second in Lausanne, Switzerland. An archival paper describing research done under this AFOSR contract was presented at each meeting. An extensive trip report was submitted each of those two years to AFOSR, which described technical developments at the conference, and the

Principal Investigator's visits to European plasma-related laboratories before and after these conferences.

Finally, during the fifth year of this contract, it was used as a vehicle for a pilot program, sponsored by AFOSR, to support undergraduate students as research assistants affiliated with AFOSR contract research in the UTK Plasma Science Laboratory. Six students were hired under this pilot program during the summer of 1985. The program was extremely successful in terms of furthering the research objectives of our contract, and introducing engineering students to ongoing experimental research programs in the plasma laboratory.

Utility of Results to the Air Force

The steady-state electric-field-dominated classical Penning discharge may be a test bed to study physical processes that occur in weapons-related intense microwave radiation and particle beam sources which are pulsed on time scales to short to allow ready investigation of their physics. The observation, during the first and second year of this contract, of broad-band, white-noise like RF emission over frequencies from 0.5 MHz to 2 GHz, was suggestive that this manifestation of the two interpenetrating beam instability might be useful for jamming communications, or for electromagnetic noise generation. Indeed, the emissions from the Penning discharge plasmas in the UTK Plasma Science Laboratory were capable, under the right conditions, of jamming both AM and FM radio reception in

Ferris Hall, where the Electrical Engineering Department and the Plasma Lab are housed. Quantitative measurements undertaken in the second and third year of this contract indicated that the intensity of the RF emission was proportional to the electron number density rather than to the electron number density squared. This is characteristic of an incoherent radiation process in which each electron radiates power independently, rather than a collective, dipole-like emission in which intensity is proportional to the square of the number of electrons participating. Moreover, the overall efficiency of the emission process, defined as the integrated RF power divided by the dc input power to the classical Penning discharge, was on the order of 0.1% or less, and had a functional dependence such that the emitted power decreased with increasing plasma density.

Other results of this program may be of utility to future Air Force programs. The production and maintenance of steady state, high power density plasmas for such military objectives as weapons effects, high power lasers, and directed energy weapons may benefit from our observation and level of understanding of anomalous plasma resistivity due to plasma turbulence, and collisional magnetic pumping. During the third and fourth year of this experimental program, radial and axial profile measurements were made of the electrostatic potential, number density, and electron temperature of the classical Penning discharge. It was found that, under highly turbulent plasma conditions, axial electric fields, parallel to the magnetic field lines, were as high as several hundred volts per centimeter in this plasma. The implied electrical conductivities of these plasmas is

anomalous, and is several hundred to several tens of thousands of times higher than the conductivity to be expected from binary collisional processes.

The very encouraging theoretical analysis which was performed in the fifth year of this contract on collisional magnetic pumping indicates that this mode of plasma heating may be competitive with other methods, such as ohmic heating and ion cyclotron resonance heating. Collisional magnetic pumping as a plasma heating method may be particularly useful in heating a high power density plasma for energetic lasers; a slight modification of collisional magnetic pumping, in which a slug of plasma is accelerated along an axial magnetic field by a traveling wave, may be of utility in directed energy weapons.

THE UTK PLASMA SCIENCE LABORATORY

Scope of Research Programs

Course offerings and active research in the field of plasma science have been underway at the University of Tennessee, Knoxville, since 1970. The UTK Plasma Science Laboratory was set up in its present form in 1980, and occupies the entire first floor of Ferris Hall, the Electrical Engineering Department's building on the UTK campus. The UTK Plasma Science Laboratory acquired in 1980 approximately $400,000 of Plasma-related instrumentation from the NASA Lewis Research Center, which enabled us to begin a research program on electric field-dominated plasmas. This inventory of laboratory equipment has been supplemented over the last four years by used, but serviceable, surplus equipment obtained from Department of Defense installations within a half-day's driving distance of Knoxville.

The UTK Plasma Science Laboratory is equipped with a variety of operating plasma diagnostic instruments, and a large inventory of power supplies, electronic test equipment, and RF and communications-related electronic equipment and hardware which support our exploratory research efforts. The UTK Plasma Science Laboratory also has two inexpensive-to-operate steady state Penning discharge plasmas on which instruments can be developed and debugged, and on which data of unusually high quality can be taken with our existing instruemnts. A recent grant (FY 1985) of $233,743 from AFOSR under the DoD-University Research Instrumentation Program (URIP) has allowed us to purchase state-of-the-art RF network analyzers and

other state-of-the-art electronic test equipment which not only provides our students training with the latest equipment, but also makes it possible for us to take plasma diagnostic data of a quality and kind that is possible to very few other university based research laboratories.

Since 1980, the UTK Plasma Science Laboratory has been partially supported by contracts with Office of Naval Research, the Air Force Office of Scientific Research, the National Science Foundation, and the Tennessee Valley Authority. In calendar year 1985, the total budget of the UTK Plasma Lab was just under $500,000. The UTK Plasma Science Laboratory is affiliated with the Electrical Engineering Department of the University of Tennessee in Knoxville, and focusses its research efforts on steady-state, electric field-dominated plasmas. Our emphasis on steady state plasmas makes it much easier for us to take diagnostic data of high quality, and to vary parameters in an exploratory way to identify and study the physical processes which occur in these plasmas. The emphasis on electric field dominated plasmas (those plasmas having strong radial and/or axial electric fields penetrating them) has allowed us to focus on an area of plasma science which has been neglected both within the DoE's fusion program, and by other university research groups in the field of plasma science. Particular electric field dominated plasmas under study in the UTK Plasma Science Laboratory include the orbitron maser, which is of interest because of its capability to produce sub-millimeter microwave emission at power levels in excess of one watt; and plasmas generated by Penning discharges, which are highly turbulent, and provde a convenient test bed for research on plasma

turbulence, anomalous electrical resistivity, and collisional magnetic pumping as a plasma heating technique.

Since 1980, the UTK Plasma Science Laboratory has established a record of new discoveries, archival publications, and interesting experimental results of which we are proud. Among our recent accomplishments are the following:

1. Joint discovery of the goemetric mean plasma emission by Professors J. Reece Roth and Igor Alexeff, followed up by archival publications (Refs. 1,2), and by a series of investigations in the UTK Plasma Science Laboratory during the first, second and third years of this contract. As part of this work, the geometric mean emission frequency was identified, and its theoretically predicted functional dependence on plasma parameters confirmed.

2. Observation of broadband RF emission from Penning discharge plasmas, at frequencies which range from below 0.6 MHz to more than 1.7 GHz. This continuum RF emission is like white noise, and represents an extreme form of nonlinear mode coupling among harmonics of the interpenetrating electron beam instability with which this emission originates. The total power in this broadband emission, under non-optimized operating conditions, ranges up to 1% of the dc input power to the Penning discharge plasma.

3. Observation of strong axial electric fields in Penning discharge plasmas. These axial electric fields have values up to several hundred volts per centimeter <u>along the magnetic field</u>, and represent a high degree of anomalous plasma resistivity. These fields provide a mechanism which

makes possible high plasma power densities, by feeding power into the plasma through the axial electric field.

4. The conception by Professor J. Reece Roth and mathematical development by Professor Roth and Mounir Laroussi, a Ph.D. student working in the Plasma Lab, of a new approach to collisional magnetic pumping. This method should be as much as several hundred times more effective than the mechanisms suggested in the late 1950's, which rely on a second order plasma heating effect. Collisional magnetic pumping is a plasma heating method which is particularly easy to apply, and may be especially valuable for heating partially ionized plasmas for high power laser applications.

5. A wide variety of plasma diagnostic instruments have been built to facilitate our research program. The UTK Plasma Science Laboratory now has one of the best-equipped university facilities in the country for the steady-state, quantitative measurement of RF plasma emissions over a wide frequency range, for the measurement of the interactions of RF radiation with plasmas, and for the measurement of plasma turbulence in the form of electrostatic potential and number density fluctuations over a wide dynamic range and over a wide range of frequencies.

<u>Laboratory Space and Utilities</u>

The UTK Plasma Science Laboratory occupies approximately 1800 sq. ft. on the ground floor of Ferris Hall on the UTK campus. This floor also has offices available with six desks for research assistants associated with the Laboratory, and a loading dock for equipment. The Laboratory is furnished

with running water, two sets of two inch supply and discharge mains at city water pressure for cooling of the magnetic field coils; city sewers; 70 KVA of 440 volt three-phase electrical power; 120 KVA of three-phase, 220 volt electrical power, fluorescent lighting, air conditioning, tile floors, and building services. In addition, the Plasma Science Laboratory has available approximately 400 sq. ft. of office and light-duty research space on the 5th floor of South Stadium Hall, under the nearby football stadium.

The Electrical Engineering Department offers further services and facilities, including a student machine shop, an electronic parts store, a technical services shop which can maintain and repair equipment, secretarial services, an IBM copy machine, a Xerox 8010 Star word processor with a laser printer, and a wide range of computational facilities.

The impact of the AFOSR contract on the UTK Plasma Science Laboratory can be seen by comparing Figure 1 and Figure 2 below. On Figure 1 is shown the UTK Plasma Science Laboratory in early 1981, before funding by the AFOSR contract. The Magnion coils, which had recently been obtained as a surplus donation from the Oak Ridge National Laboratory, are at the center of the floor. No funding was available to repair its dc power supply, to furnish cooling water, or set up the necessary glass vacuum system. When the contract was announced, the University supplied the necessarry water connections shown in Figure 2. Figure 2 is a recent photograph of the AFOSR equipment shown in Figure 1, with the vacuum system in place, and the electrical and water cooling lines connected.

FIGURE 1

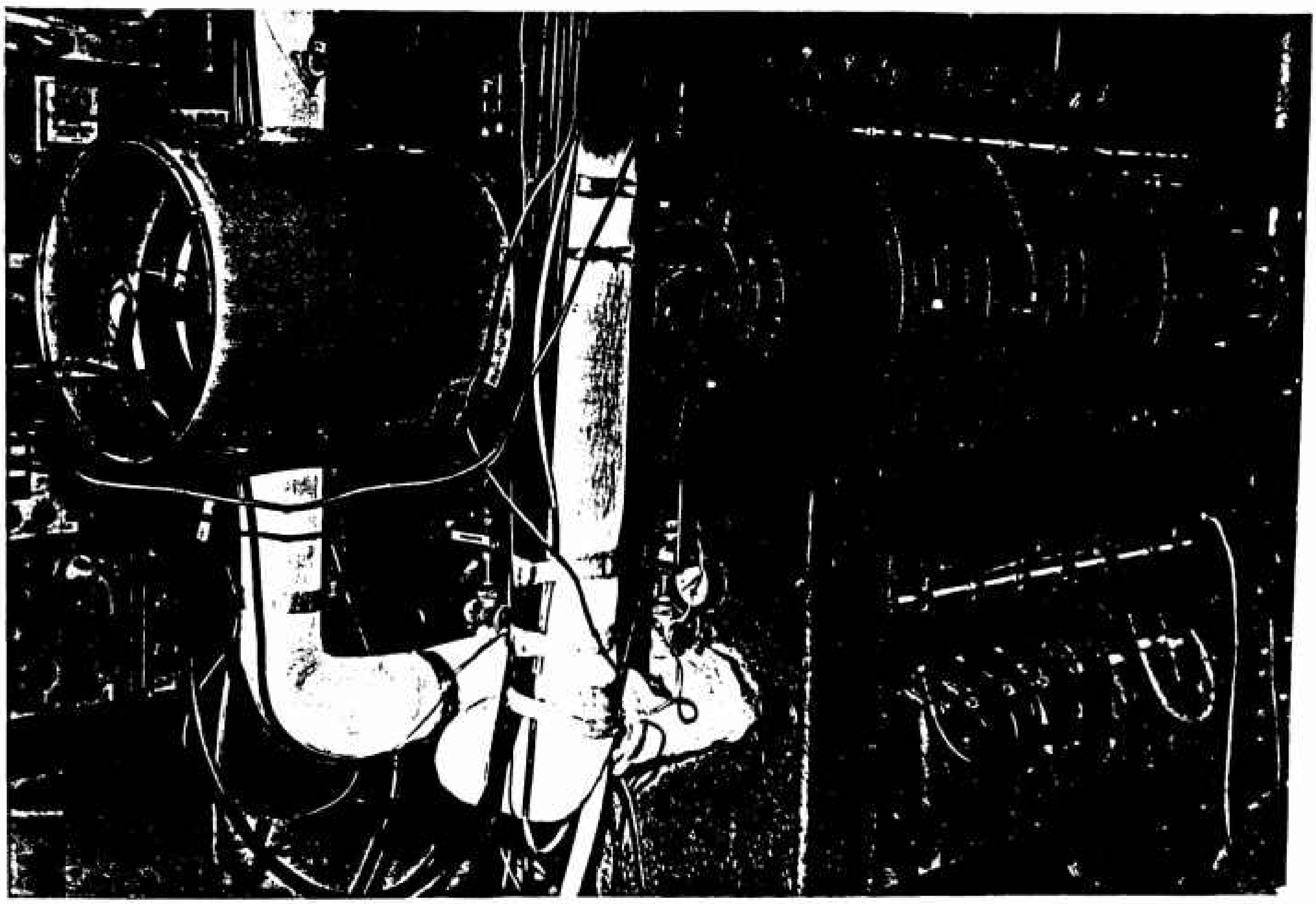


Figure 2

On Figure 2 is a photograph of the AFOSR classical Penning discharge apparatus. Most visible are the seven-inch ID Magnion water-cooled copper coils on the right center. The glass vacuum system which threads the bores of these coils is visible to the right and left of these magnets. The cooling water lines are visible to the left, and the large cylindrical structure to the left center is the plastic safety shield over the high voltage electrode connection. The coils in this array are spaced in such a way that the magnetic field in the plasma containment volume, between cathodes of the Penning discharge, is uniform to within ± 1 percent.

Impact of AFOSR-URIP Equipment Grant

In 1983 we submitted a proposal to the AFOSR for $233,743 to buy new, state-of-the-art equipment for our AFOSR research effort in the UTK Plamas Science Laboratory. Most of this money was to be spent on low and high frequency network analyzers to make possible highly sophisticated active and passive plasma diagnostics. In April, 1984 we were pleased to learn that this proposal was fully funded with fiscal year 1985 money. This money became available to us in January, 1985.

Preparations for purchase of this equipment started in the late Fall of 1984, and were conducted primarily by Prof. David Rosenberg, a portion of whose time was supported by this contract. Searching the catalogs, and negotiations with the Hewlett Packard Corporation occupied much of our time during December, January, and February of 1984-85. An order for the low

frequency and microwave network analyzers was placed with the Hewlett Packard corporation in March, 1985. At this writing, approximately 90% of the equipment, in terms of its cash value, has been delivered and tested. We were able to get a good price on most of this equipment by utilizing consignment equipment, which had been used as demonstrator models at trade shows etc.. However, this equipment is otherwise new and has the same warranty, calibration, and testing as new equipment.

According to the Hewlett Packard representative, the network analyzers which we purchased represent the most sophisticated and highest-tech item in the Hewlett Packard equipment inventory. In order to run this equipment, Prof. Rosenberg and a research assistant from the UTK Plasma Science Lab took a special course in Atlanta, Georgia in August, 1985. The new instrumentation which we intend to buy should greatly facilitate the measurement of RF emissions above 1 gigahertz, and make possible quantitative measurements, which heretofore have been extremely difficult, at frequencies up to 20 GHz.

Impact of DoD Surplus Equipment

During the period covered by this report, the Principal Investigator and one or more of the research assistants associated with this contract have made eight screening trips to DoD installations within a half-day driving range of Knoxville. These screening trips were initiated in December, 1982, and have continued as we build up an inventory of microwave and electronic test

equipment of a kind which facilitates exploratory basic research in our general area of interest: RF interactions with electric field dominated plasmas. The screening trips have served the primary function of filling gaps in the microwave hardware needed at various wavelength bands, and picking up isolated pieces of test equipment that we need for our research program.

Specalized Research Equipment Used on This Contract

Over the past five years, the UTK Plasma Science Laboratory has built up an inventory of specialized research equipment, plasma diagnostic instrumentation, and computerized data reduction capabilities that are, if not unique, at least well above average by university standards. Among the specalized equipment at the UTK Plasma Science Laboratory available for our research program is the following:

1. A 20 centimeter inside bore, 0.35 tesla, 18-coil, water-cooled solenoid complete with power supply, cooling water, and a control system capable of providing steady state magnetic fields for plasma research. This facility is currently dedicated to the ONR experiment, the contract for which will expire on October 1st, 1987.
2. A 17 centimeter inside diameter, 0.50 tesla, 8 coil water-cooled solenoid, with power supply, cooling water, and control system. This facility is used in the current AFOSR research contract for the classical Penning discharge, and is capable of providing a steady state magnetic field for plasma research.
3. Both of the above mentioned magnet systems are furnished with glass vacuum systems, which allow flexibility in rearranging diagnostic probes and

sensors. The glass vacuum systems also allow electrostatic potential fluctuations and RF emissions from the plasma to be detected outside the vacuum system. Each of these vacuum systems has a refrigerated cold trap, using a special freon which achieves -100 degrees centigrade, and each system can reach base pressures in the mid or low 10^{-6} torr range. Each vacuum system also has a turbo-molecular vacuum pump which reduces the background contamination which would otherwise occur from diffusion pump oil. These vacuum systems have been in operation for several years, are throughly debugged, and are extremely reliable research tools.

4. The UTK Plasma Science Laboratory has available a 40 kilovolt, 1 amp dc high voltage power supply which is used to energize the Penning discharges on the current AFOSR and ONR experiments. This power supply has safety interlocks, overcurrent and overvoltage trip protection, and allows the output voltage to be varied from a few hundred volts to a maximum value of 40 kilovolts, while drawing up to 1 amp of current. This power supply uses vacuum tube electronics, and therefore operates reliably in spite of the occasional arcs characteristic of steady state Penning discharge plasmas.

5. A major recent addition to our inventory of specialized research equipment is a Hewlett-Packard model 8510 high frequency network analyzer which is capable of operating from 45 MHz to 18 GHz. This network analyzer was purchased with part of the DoD-University Research Instrumentation Program grant awarded to the UTK Plasma Science Laboratory. This analyzer allows us to measure the frequency response and impedance function of microwave equipment over the frequency range of the instrument. It

facilitates absolute measurements of RF power, and turbulence measurements over a dynamic range of 80 dB. To our knowledge, no other university-based plasma research laboratory in the country possesses such an instrument.

6. As part of the instrumentaiton purchased with the AFOSR-DoD-University Research Instrumentation Program grant, we also bought a Hewlett Packard model 3577 low frequency network analyzer, the frequency response of which ranges from 5 Hz to 200 MHz. This network analyzer can be used for calibration of absolute signal levels, and for measuring the frequency response of our diagnostic equipment.

Plasma Diagnostic Instrumentation

During the past five years, the UTK Plasma Science Laboratory has built up an inventory of plasma diagnostic instrumentaiton which makes it well-equipped by university standards. Some of this instrumentation is the first of its kind and has been documented in the literature. These publications are listed in Appendix C. The most notable items of our diagnostic instrumentation are the following:

1. Vacuum Mass Spectrometer - The vacuum system used for the classical Penning discharge is equipped with a vacuum mass spectrometer which not only allows us to detect leaks in the vacuum system, but also confirms that the gas in the vacuum system during an experiment is that intended.

2. Capacitive Probes - On Figure 3 is shown a photograph of a dual capacitive probe system used in the UTK Plasma Science Laboratory. The

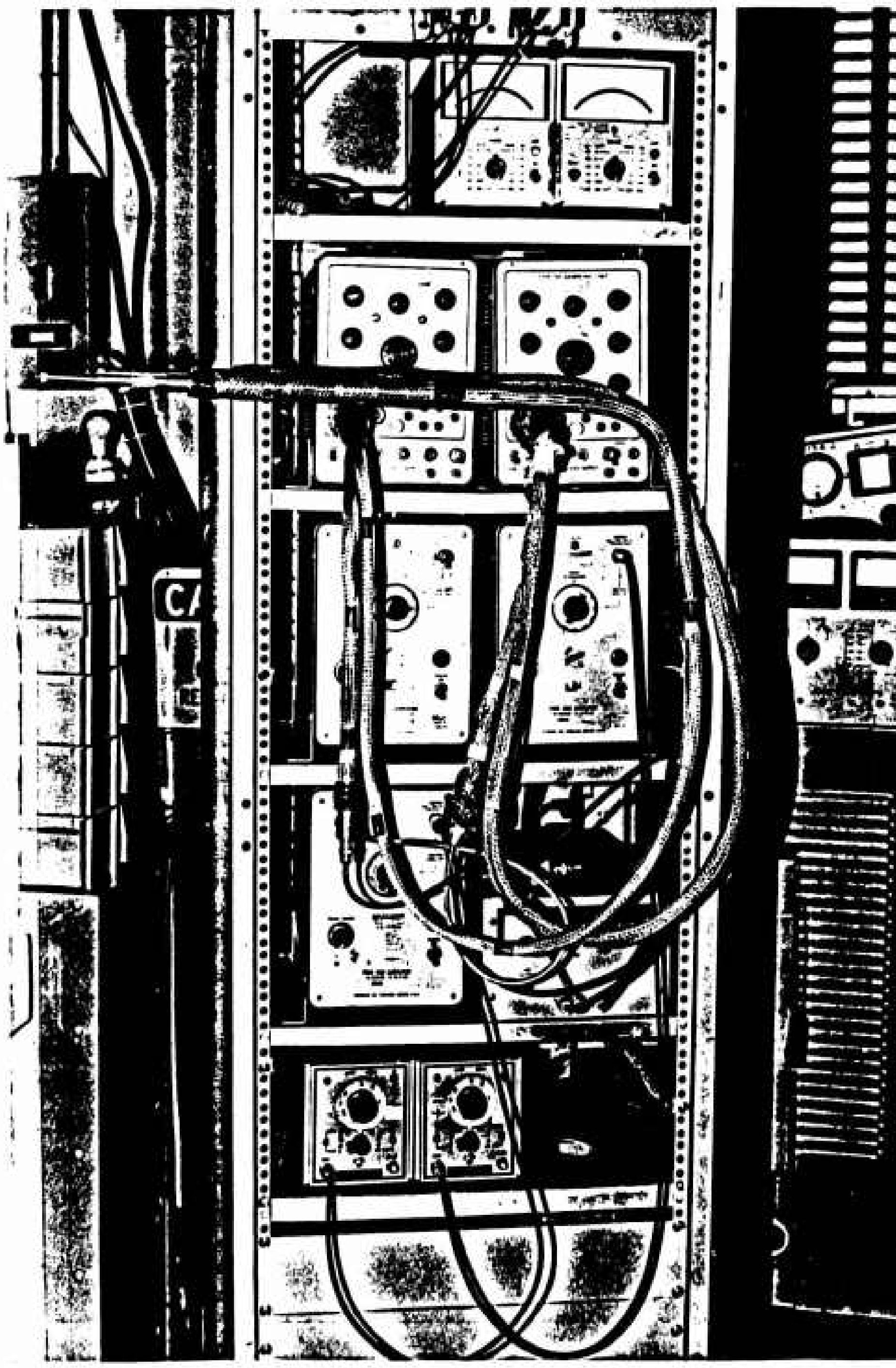


Figure 3

two capacitive probes are resting horizontally in the upper portion of the photograph; the equipment rack contains the power supplies for the probes, and the amplifiers and filters which are part of the data handling system for these probes. These probes have a frequency response which is virtually flat from 1 kilohertz to 10 megahertz. These probes can be positioned at various locations immediately outside the glass vacuum system, where they can detect the electrostatic potential fluctuations associated with plasma instabilities and turbulence. Under other conditions of operation, capacitive probes are inserted into the vacuum system, and are positioned in the vicinity of the plasma boundary.

3. Langmuir Probes - The UTK Plasma Science Laboratory has a number of Langmuir probes and a high voltage Langmuir probe power supply system which is used for measuring plasma parameters. An unusual problem encountred in these electric field dominated plasmas is that the plasma potential is often quite high, on the order of kilovolts. For this reason, it is necessary to bias the Langmuir probe to several kilovolts in order to take a Langmuir probe curve which will allow us to measure the electron kinetic temperature and number density. We have developed a data handling system which will take the Langmuir probe traces automatically, and print out, on line, the plasma parameters based on the Langmuir probe trace. This software development is described in the next section. A photograph of the LeCroy 3500 computer, with a Langmuir probe trace on the screen, is shown in Figure 4, along with Saeid Shariati, the graduate student who developed this software program for his Master's thesis.

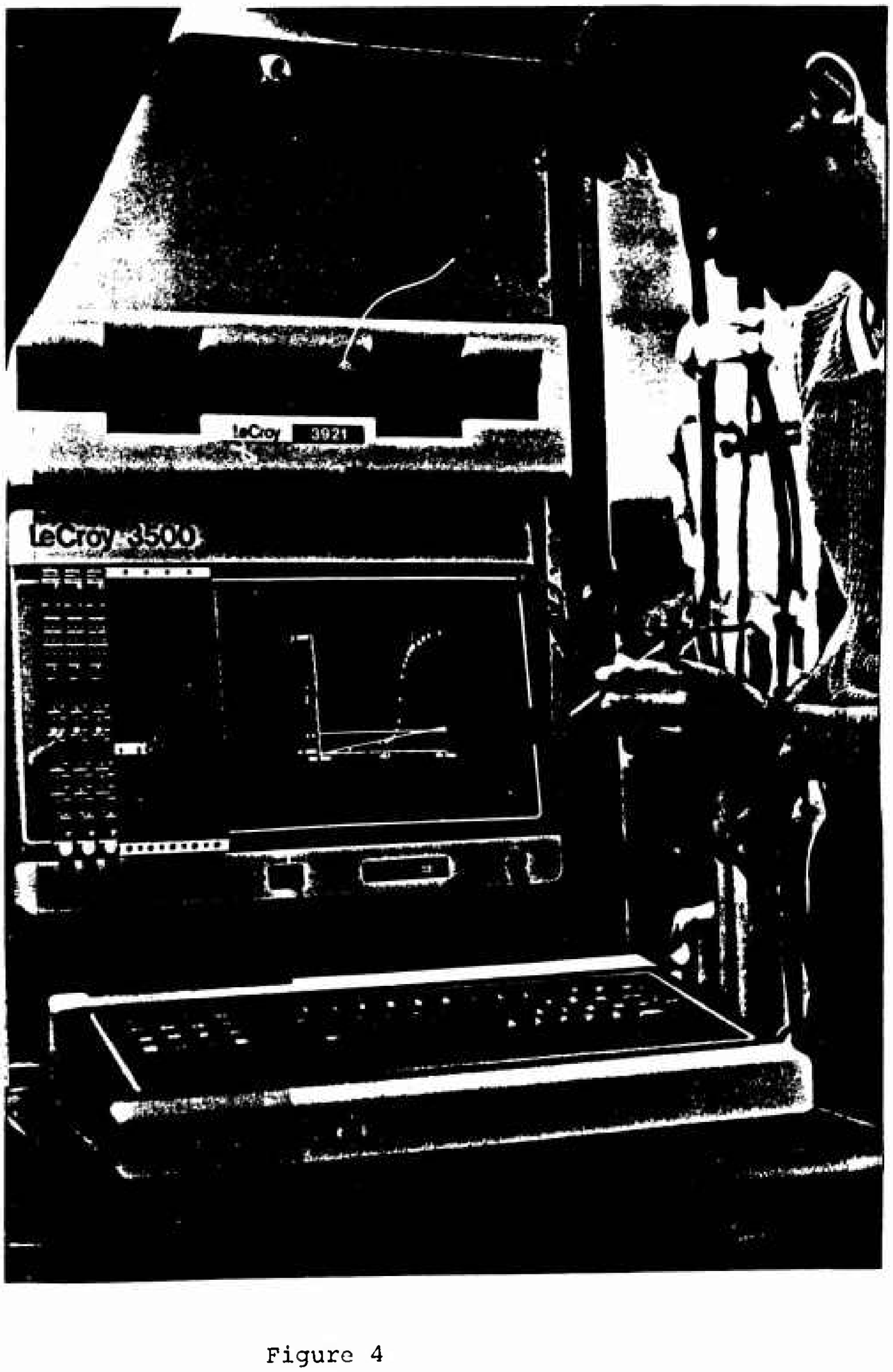


Figure 4

4. Retarding Potential Energy Analyzers - The vacuum system used for the classical Penning discharge has a retarding potential energy analyzer permanently installed. When data are taken, this analyzer is energized by an external power supply on an equipment rack. The retarding potential energy analyzer is used to measure the integrated energy distribution function of ions lost along the axis of the magnetic field in the two Penning discharges.

5. A Polarization Diplexing Microwave Interferometer - This instrument was developed in collaboration with Prof. Andrew L. Gardner of Brigham Young University. This instrument can use both modes of polarization of the microwave radiation at 28 GHz, and can detect densities as low as 10^8 electrons per cubic centimeter.

6. Analog-to-Digital Data Handling System - The UTK Plasma Science Laboratory has an analog-to-digital data handling system based on the LeCroy 3500 SA system, shown in Figure 4, with three type 8837, 32 megahertz transient recorders. The LeCroy system is capable of taking three simultaneous channels of data, and digitizing them at rates up to 32 MHz. This digitized data can be displayed on the screen of the LeCroy model 3500 SA, and then sent by a hard-wire data link to the Electrical Engineering Department's VAX 780-11 computer for analysis by appropriate software programs.

7. Calibrated, Broadband Antennas - As part of our on-going research program to measure RF plasma emissions, we have developed two calibrated, broadband antennae, which have a very broad and flat frequency response, from approximately 100 MHz to 1.2 GHz. In addition, they have been

absolutely calibrated to measure the incident power, in watts, received from our plasmas. The instrumentation and hardware necessary to make and implement these absolute calibrations have also been developed, and include the HP 3577 low frequency network analyzer, described in the previous section.

8. Other Research Equipment - In addition to the above individual items of plasma diagnostic equipment, the UTK Plasma Science Laboratory is well equipped with a variety of power supplies, RF voltmeters, signal generators, microwave hardware and accessories, and other equipment necessary to do RF detection and plasma research. Over the years, we have built up our inventory of research equipment through the DoD Surplus Property Utilization Program, which makes available used but serviceable equipment to DoD contractors. This has allowed us to obtain equipment useful for exploratory research which we could not afford otherwise.

Specalized Data Reduction Capabilities

At the UTK Plasma Science Laboratory, we have attempted to stay at the leading edge of the development of plasma diagnostic software and digital data handling and reduction methods. The resources of our Electrical Engineering Department are very valuable in this respect. Some of the hardware and software which we employ are as follows:

1. The VAX 780-11 Computer - This computer is installed in Ferris Hall, and is readily available to users in the Electrical Engineering Department. There are four hardwired data links from the VAX computer to the UTK

Plasma Science Laboratory, three of which are presently connected to terminals and/or the minicomputers described below. This computer makes available on-line data reduction of fairly sophisticated programs, the running of which on our minicomputers in the Plasma Lab would either take too long, or not be possible.

2. A HP 9836 Series 200 Minicomputer - The primary function of this unit is to run the HP 3577 and HP 8510 network analyzers in their fully automated mode. It can also be used as a stand-alone computer for other data handling and data processing tasks. This computer is connected by a hardwired link to the EE Department's VAX 780-11 mainframe computer.

3. A LeCroy 3500 SA Minicomputer - The LeCroy Minicomputer was described previously, and is used as a three channel, 32 MHz transient recorder and digitizer system with three LeCroy model 8837 transient recorders. In addition, the LeCroy system has a four channel, 1 MHz model 8501 analog-to-digital converter which is used at lower frequenies, when the system is used as a smart X-Y plotter or oscilloscope. The LeCroy 3500 SA minicomputer is connected by a hardwired data link to the EE Department's VAX 780-11 mainframe computer, and can transmit digitized data to that computer for analysis by various software programs.

4. A Tektronix Model 4002A Graphics Terminal - This older unit was obtained surplus from the NASA Marshall Space Flight Center in Huntsville, Alabama, and is used as a graphics terminal by our graduate assistants to communicate over a hardwired link with the EE Department's VAX 780-11 mainframe computer.

5. Software for Plasma Turbulence Analysis - The software required to analyze the statistical properties of simultaneously sampled signals is based on a time series analysis computer program very generously furnished to us by Prof. E. J. Powers of the Unviversity of Texas, Austin. This program has been modified for use on the EE Department's VAX 780-11 mainframe computer. This program has the capability of displaying such statistical properties of the plasma fluctuations as the auto and cross power spectra of two simultaneously sampled channels, phase spectra of the fluctuations between two channels, the coherence spectra, and finally it also contains the output software package required to plot the calculated data.

6. Computerized Reduction of Langmuir Probe and Retarding Potential Energy Analyzer Data - The LeCroy model 3500 SA transient recorder system has been modified to act as a smart X-Y plotter, to do real time, on-line data reduction from such diagnostic instruments as Langmuir probes, retarding potential energy analyzers, capacitive probes, and charge exchange neutral energy analyzers. The software required to support this and similar plasma diagnostic data reduction systems was not available from LeCroy or any other manufacturer. Mr. Saeid Shariati, a former graduate student in the Department of Electrical Engineering (who now works for the General Electric aircraft engine plant in Cincinatti, Ohio), has, for his master's thesis, developed software for the LeCroy 3500 transient recorder system which reduces data from a retarding potential energy analyzer and the high voltage Langmuir probe system, as well as our charge-exchange neutral energy analyzer system.

Some results of the data reduction program are shown in Figures 4 and 5. Figure 4 shows the printout of the raw Langmuir probe curve on the LeCroy model 3500 display screen. By using an interactive light pen, the investigator may designate the data which are to be analyzed by the software program, and the boundaries of the ion saturation regime of the Langmuir probe curve. A best-fitting straight line is fit automatically to the data in the ion saturation regime, and the difference between this extrapolated ion saturation line and the probe current is taken to obtain the electron current to the probe. The electron current is plotted against probe potential on the semi-log plot shown in Figure 5. The limits of the straight line portions of the semi-log curve in Figure 5 are designated by the investigator with the light pen. The slope of the straight line portion determines the electron kinetic temperature of the plasma. The investigator then also designates the upper and lower limits of the electron saturation regime, to which the computer program automatically fits a straight line. The intesection of these two straight lines is, following normal practice in the reduction of Langmuir probe data, taken as defining the plasma potential at the electron saturation current. Once these portions of the curve are identified on the screen of the LeCroy 3500 by the light pen, the computer program automatically determines the plasma parameters which can be obtained from a Langmuir probe, including the electron kinetic temperature, the floating potential of the probe, the plasma potential, the electron number density, and the ion kinetic temperature. A similar software program is available to reduce data from the

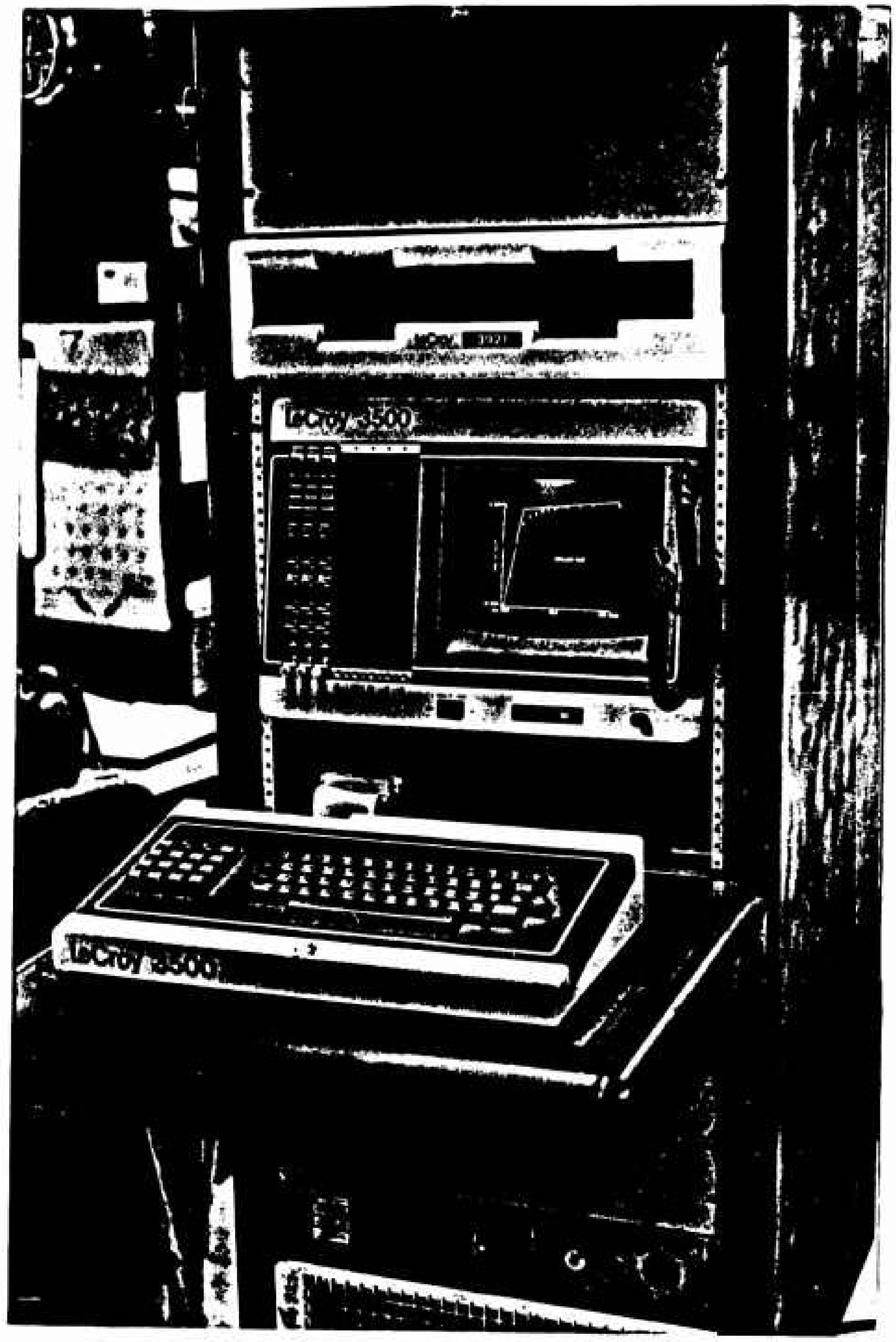


Figure 5

retarding potential energy analyzers, and also from a charge exchange neutral energy analyzer.

Weekly Plasma Seminar

An important part of our research activities at the UTK Plasma Science Laboratory is a weekly Plasma Seminar in which the senior faculty and all research assistants participate, along with undergraduate students and any one else who is interested. Our graduate research assistants are expected to give at least one, one hour-long seminar on their work during each quarter, and in addition we obtain outside speakers from the Oak Ridge National Laboratory or visitors to the campus to supplement our seminar schedule. The nature of this weekly seminar can best be appreciated by looking over some of the topics which were covered in the academic years covered by this contract. Copies of our seminar schedule are included in Appendix H of this report.

RESULTS OF EXPERIMENTAL RESEARCH PROGRAM

This research program was initiated on March 15, 1981, and spanned a total of 5 years. It was supported by AFOSR contract 81-0093 under NP program manager Dr. Robert J. Barker of the Bolling Air Force Base. This contract was a new start at the University of Tennessee, Knoxville, and is an important part of our efforts, at the UTK Plasma Science Laboratory, to conduct research on electric field dominated plasmas, and to investigate the physical processes associated with RF emissions and plasma heating and turbulence in these plasmas.

The objectives of this contract were as follows:

1. To operate for experimental investigation a steady-state classical Penning discharge which creates an electric field dominated plasma penetrated by strong radial and axial electric fields.
2. To optimize the operation of this Penning discharge to produce phenomena of interest, including radio frequency emissions at the geometric mean emission frequency and other frequencies; anomalous plasma resistivity; and ion heating by the application of raw DC electrical power.
3. To determine the most effective electrode geometry, axial magnetic field profile, and plasma operating conditions which produce the phenomena of interest.
4. To develop dedicated plasma diagnostic instruments to measure the phenomena of interest, where such instruments are not already in the inventory of the UTK Plasma Science Laboratory.

5. To measure the parallel and perpendicular plasma resistivity, and compare these values with theoretical predictions.

6. To conduct exploratory studies of RF emissions, to determine whether any unanticipated phenomena are present.

7. To conduct theoretical studies of beam-plasma interactions, to provide insight into phenomena observed in the laboratory.

Summary of Technical Results, 1st Year

All of the necessary formalities were complete in time for contract AFOSR-81-0093 to start on March 15, 1981. Upon signing the contract, we were able to place orders for required vacuum equipment, and arrange for the University to begin the plumbing and electrical work necessary to install the magnetic field coils for the AFOSR contract, at no expense to the Air Force.

The rectifier power supply for the coils was made by the Sel-Rex Corporation 25 years ago, and no documentation was available when this coil system was obtained as a donation from the Oak Ridge National Laboratory. A complete wiring diagram was drawn up by Mr. Roger Richardson, our summer research assistant, who also repaired the control system. The power supply ws hooked up to water and electrical power. The power supply was tested and produces 900 amps of direct current when connected to the coils.

Final assembly and operation of the vacuum system was delayed until mid-February, 1982, by the procurement of a special piece of 5 inch diameter glass pipe which threads the inner bores of the magnetic field coils. The

vacuum system was fitted with a turbomolecular pump which was purchased with equipment money designated in the first year of this contract. The first plasma was achieved in February, 1982, and this was followed by several weeks of exploratory investigations.

After achieving the first plasma, our first priority was to bring on line the diagnostic instruments necessary for our research program. This proceeded rapidly, thanks to the facilities and equipment already available at the UTK PLasma Science Laboratory. On the same day we achieved the first plasma, it was possible to make measurements of the RF emission spectrum, since the spectrum analyzers required were mounted in a mobile equipment rack and were easily borrowed from the ongoing investigations for the ONR contract. A retarding potential energy analyzer, identical to that used in the ONR contract, was installed in the vacuum system, and, when required, connected to the same power supplies, ramping circuits, and xy recorder used for the ONR experiment. Available equipment was used to fabricate a high voltage Langmuir probe (needed because floating potentials up to 10 kV must be measured) for potential profile measurements.

During this first year, the AFOSR magnet facility was set up to produce a classical Penning discharge configuration (Refs. 3, 4), in which the magnetic field is approximately uniform along the axis of the discharge. This configuration lacks the magnetic field minimum in the vicinity of the anode of the discharge which is characteristic of the modified Penning discharge. The classical Penning discharge was operated with a uniform magnetic field up to 0.3 Tesla at the Penning anode, and produced a plasma about 10 centimeters

in diameter and 70 centimeters long. The plasma was operated in the steady-state with helium and argon gas, and the glass vacuum system allowed RF radiation to escape.

Some of the initial experimental results are illustrated in the Interim Scientfic Report for the first year. A spectrum of RF emission from 0 to 500 MHz revealed 27 harmonics extending out to 500 megahertz. Harmonics have been observed under other conditions to 1 MHz. Many nonlinear mode coupling phenomena were apparent, including an example of plasma "lability" in which the spectral amplitude is greatest around the 8th harmonic at 200 MHz. This maximum in the envelope of harmonics of the geometric mean emission frequency occurs at the electron plasma frequency for the discharge.

Summary of Technical Results, Second Year

In early Summer, 1982, a high voltage Langmuir probe capable of being moved along the plasma axis was installed and put into operation. This instrument yielded axial profiles of electrostatic potential as well as simultaneous data on electron kinetic temperature and number densities. An antenna provided data on RF emissions, and axial ion energy spectra were measured by a retarding potential energy analyzer. A publishable set of data were taken in October, 1982 and were presented at the APS Plasma Physics Division meeting in New Orleans in November, 1982. During the period from November, 1982 to the end of January, 1983, the apparatus was disassembled

and modified to provide a more uniform axial magnetic field; to install larger diameter glass tubing in the vacuum system and hence allow a larger plasma diameter; to make additional provisions for cooling the cathodes of the discharge, where the greatest heat deposition takes place; and the retarding potential energy analyzer and Langmuir probe systems were decoupled, so that they now use independent power supplies and can both be operated simultaneously. The vacuum system was reassembled and put back into service in early February, 1983. The plasma functioned in a new regime of operation involving up to 700 watts of power input, 0.7 amperes of current, and number densities that exceeded 10^{10} particles per cubic centimeter throughout the plasma volume.

Spectra of the RF emission from 0 to 1 GHz were taken as a function of the neutral background pressure of argon gas. As the pressure increases, the nonlinear mode coupling seems to increase, and gives rise to RF emission above 500 MHz. Finally, at very high pressures, the RF emission falls to low levels. Spectra of the RF emission from argon gas over frequencies from 0 to 1 GHz were measured for values of the background magnetic field strength which span a factor of 2. The amplitude of the RF emission, and the degree of nonlinear mode coupling, increased dramatically with magnetic field strength. This phenomenon was observed also on the modified Penning discharge operated for the ONR contract, and represents a somewhat surprising and counter-intuitive result. It appears that the addition of a constraint to the system, in the form of an increasingly strong magnetic field,

will increase the RF emission amplitudes, and promote the nonlinear processes which are responsible for coupling energy to higher frequencies.

During these investigations, RF detection equipment was used at frequencies of 10, 35, and 70 GHz. No emissions were observed under the operating conditions existing at the time. In addition, a panoramic spectrum analyzer which covers the range from 1 GHz to 28 GHz was borrowed from Professor Alexeff's AFOSR contract, and this instrument indicated no RF emission above 1 GHz, for the particular conditions observed. All of the detectors above 1 GHz, however, were relatively insensitive, (by a factor of about 20) compared with the antenna and detection system on our 0 to 1 GHz spectrum analyzer.

The above preliminary findings were followed in the summer and early fall of 1982 by a series of investigations of the potential profile and the ion energy distribution functions in the classical Penning discharge. These findings were reported at the APS Plasma Physics Division meeting in November, 1982. The emphasis of these data was the simultaneous measurement of the floating potential profile along the axis of the discharge, and of the axial ion energy distribution function with a retarding potential energy analyzer located beyond the cathode at one end of the discharge. The floating potential on the plasma axis was about 2300 volts when approximately 3100 volts was applied to the midplane anode ring. A radial potential drop of 800 volts occured across the plasma radius and/or in the sheath between the plasma and the midplane anode ring. Most of the axial potential drop occured within 5 centimeters of the cathode, a conventional

sheath effect. The retarding potential curve for the integrated ion energy distribution function under these conditions has a best-fitting ion kinetic temperature of 2.9 keV. The actual experimental data depart from this Maxwellian distribution, and have a small monoenergetic peak near the anode potential of 3.1 kilovolts.

When this discharge was operated under relatively high pressures, an interesting structure began to develop in the axial potential profile for high pressure operating conditions in argon gas, with an anode voltage of 3100 volts. The potential on the axis was about 1 kilovolt below that of the anode, and a small potential well, of at least 200 volts, was evident on the retarding potential curve for these conditions. Finally, at very high pressures, a significant potential well for ions develops near the midplane of the discharge. The axial electric fields associated with this potential minimum are about 50 volts per centimeter. The origin of these potential wells, and the factors which promote their formation and maintenance are yet to be fully understood.

The results taken during the period from February 1, 1983 to March 15, 1983 were reported at the 1983 IEEE International Conference on Plasma Science, held May 23-25, 1983 in San Diego.

On Figures 6 and 7 are two RF emission spectra taken when the plasma was operating in the high power mode. The first of these shows the emission spectrum from 0 to 1.2 gigahertz. The vertical scale is 10 dB per centimeter. The intensity of RF emissions is approximately a factor of 100 higher than they were in the lower density and lower current configuration operated earlier. The emission shown in Figure 6 has a broad maximum around a

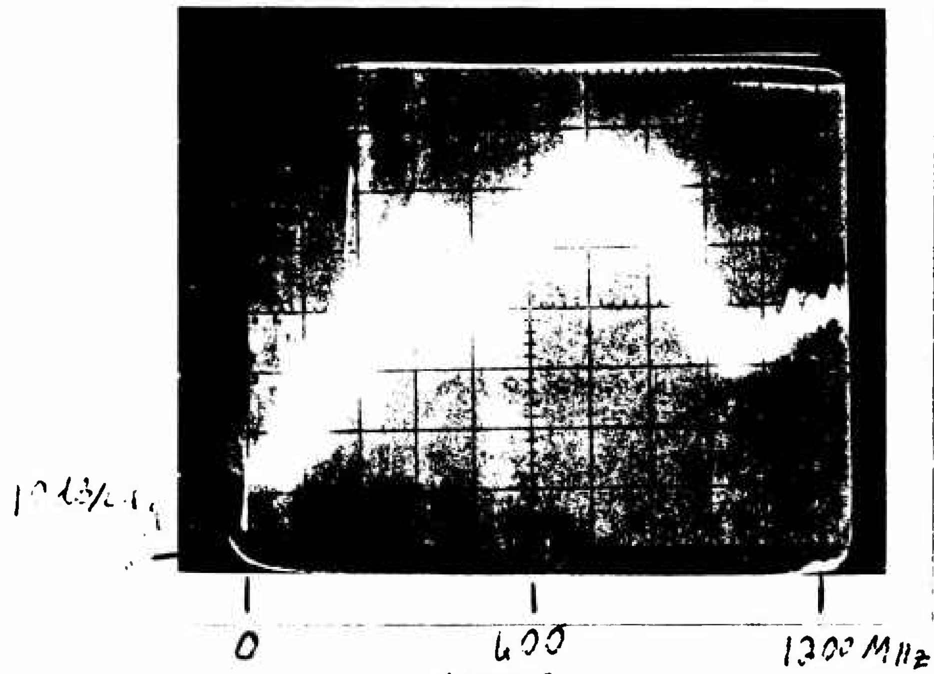


Figure 6

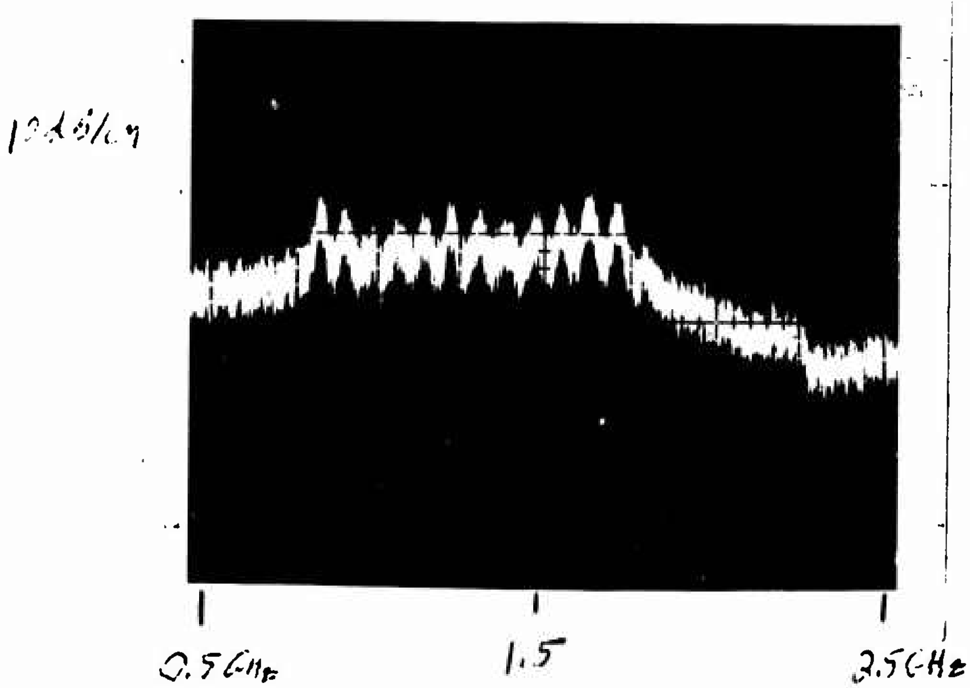


Figure 7

Run C5-02

V_a = 1.45 kV
I_a = 330 mA
I_c = 390 amps
p_o = 1.4 x 10^{-4} torr gauge

frequency of approximately 700 MHz, and is present above the upper limit of 1.2 GHz. The structure on the RF emission spectrum is not random in character or due to inadequate video filtering; retracing of the spectrum with a manual scan shows that the peaks are reproducible, and present in the steady-state. These peaks are harmonics of the geometric mean emission frequency, the fundamental of which is about 40 MHz. The peak at approximately 700 megahertz is consistent with the electron plasma frequency of the discharge.

To determine the upper limit of the RF emission of this plasma, we borrowed from Professor Igor Alexeff the high frequency spectrum analyzer which he purchased under his AFOSR contract. On Figure 7 is shown an RF spectrum over the range from 0.5 GHz to 2.5 GHz. Emissions are clearly evident in the band from about 1 GHz to 1.8 GHz. The RF emissions are above the base line at 2 GHz.

Summary of Technical Results, Third Year

At the beginning of the period covered by the report, the experimental program was devoted to taking a simultaneous, publishable set of axial profile data from the classical Penning discharge, which included measurements made under the same operating conditions, and at the same time, of axial profiles of electron number density, electron kinetic temperature, plasma potential, and floating potential taken from the Langmuir probe used to make the other measurements. These profiles documented both the plasma

parameters along the axis of the Air Force classical Penning discharge, and the existence of very strong axial electric fields under some conditions of operation. At the same time that these axial profiles of plasma parameters were measured, the emission of RF radiation over the range from 100 to 1200 MHz was simultaneously measured. These data were presented at a paper at the Americal Physical Society's Plasma Physics Division in November, 1984.

After the completion of this phase of our research program, we turned our attention to microwve scattering measurements in this discharge. Mr. Larry Baylor initiated a research program involving microwave scattering of a 32 GHz signal from the highly turbulent plasma of the classical Penning discharge. The experimental apparatus was based on 32 GHz microwave components already available in the UTK Plasma Science Laboratory, and was quickly assembled, debugged, and placed into operation. Mr. Baylor was able to observe very strong signals from the scattering of microwave radiation, over scattering angles from 20° to 160°, from the propagation direction across the plasma diameter. These experimental investigations were written up for June graduation, 1984.

In the year following March 15, 1983, several new pieces of diagnostic apparatus were put into operation, and older diagnostic systems were refined to permit more accurate measurements of plasma kinetic temperatures, number densities, and plasma potentials. A continuing effort to refine the design of our Langmuir probes has resulted in probe assemblies which can be inserted axially along the magnetic field lines, and which have a sufficiently small minor diameter that they do not significantly disturb the plasma

number density or anode current when they are used. Probes similar in design to those now used on the AFOSR classical Penning discharge were first developed for the modified Penning discharge used in the ONR contract, and validated in that apparatus against number density measurements made with a 27 GHz microwave interferometer. In addition to refinement of the Langmuir probes and probing system, we have made improvements in the probeholders for capacitive probes, in RF antennae, and in the retarding potential energy analyzer system. These improvements extend the range of measurements possible with these systems and/or greatly facilitate the ease with which more accurate data can be taken.

Most plasma diagnostic instruments are nonlinear, in that they provide signals which are not linearly related to the plasma parameters which one wishes to measure. This is particularly true of the various parameters that describe the statistical properties of plasma fluctuations; Langmuir probe traces; and retarding potential energy analyzer curves. During the period following March 15, 1983, the software required to obtain the plasma potential, the ion kinetic temperature, and the degree of departure from a Maxwellian distribution of a retarding potential curve was completed, debugged, and put into service. It is now a normal part of the diagnostic inventory of the UTK Plasma Science Laboratory. This program is written in Fortran, and is of potential utility to other users, if some way could be found to market it in a standard format. This diagnostic has confirmed the existence of ion heating to energies and/or kinetic temperatures of kilovolts.

Previous theoretical work on the geometric mean emission frequency (ref. 1, 2) was restricted to the special case of two equal and oppositely directed electron beams interacting with a cold background of ions. Professor Igor Alexeff and I were able to show that growing waves were to be expected at the geometric mean emission frequency. During the summer of 1983, we generalized this theoretical work to the case of unequal, oppositely directed electron beams interacting with a background plasma consisting of cold ions and cold electrons. This more general theoretical analysis (although restricted to the steady-state, non-relativistic limit) has revealed a wide variety of new phenomena, including a growing wave from which RF radiation can be expected to result, at frequencies above the geometric mean emission frequency. This analysis shows that if the beams are of unequal strength, which could happen in reflex discharges, waves can grow over a wide range of frequencies. This may provide an explanation of the multiple harmonics observed in Penning discharges and reported in this and previous AFOSR status reports.

For a few months after July, 1983, the experimental program on the plasma was put into a standby mode, in which the apparatus was run only occasionally for the checking out and debugging of the diagnostic instruments which were being developed. During the period from September, 1983 to March, 1984, the microwave scattering system, and the analog-to-digital data handling system were the primary focus of attention of the research assistants and thesis students assigned to the AFOSR experiment. Thse experiments started to produce publishable data at the end of this report period.

Some results from the AFOSR experiment were incorporated into a paper which was presented at the International Conference on Plamas Physics held in Lausanne, Switzerland on June 27-July 3, 1984. This four page paper is included in Appendix E. In this paper, we did a comparison of the axial profiles and RF emission of the AFOSR and ONR plasmas, generated, respectively, in a classical and a modified Penning discharge. It now appears that the existence of strong axial electric fields and high effective plasma resistivities is enhanced by the axial magnetic field gradients present in the modified Penning discharge used in the ONR experiment. On the other hand, the production of monoenergetic ions of kilovolt energies is enhanced by the uniform axial magnetic field associated with the AFOSR experimental apparatus.

Summary of Technical Results, Fourth Year

During the summer of 1984, the vacuum system was upgraded with new equipment, the purchase of which was authorized in the contract for this year. The old, unreliable ion gauge readouts were replaced with new units which have automatic ranging, and use the same ion gauge tubes employed on the ONR apparatus, and on other vacuum systems in the UTK Plasma Science Laboratory. A Polycold refrigerated cold trap system was purchased and installed on the AFOSR experiment. We also procured and installed a model 1200 Veeco mass spectrometer, which allows us to monitor the composition of the background gas in the vacuum system, and to assure that the working gas

in the plasma containment volume is that which we believe it to be. In addition, we installed a work bench and additional cabinets, and otherwise upgraded the laboratory working environment.

Most of the experimental results obtained on the AFOSR apparatus during the spring of 1984 are written up in a master's thesis by Mr. Larry R. Baylor entitled "Microwave Scattering as a Plasma Diagnostic in a Penning Discharge", the Abstract and Table of Contents of which are included in Appendix F of this report. Mr. Baylor completed a research program involving microwave scattering of a 32 GHz signal from the highly turbulent plasma of the classical Penning discharge. These experimental investigations were written up as a M.S. Thesis in E.E. for June graduation, 1984.

From early January to the end of June, 1984, final debugging and testing of the hardware and software for the analog-to-digital data handling system was accomplished, and it became possible to correlate the microwave scattering data with data from capacitive probes placed immediately outside the glass vacuum system in which the plasma was operated. These results were reported in poster papers at the IEEE International Conference on Plasma Science, held in St. Louis, MO in May, 1984, and at the International Conference on Plasma Physics held in Lausanne Switzerland in late June, 1984.

The microwave scattering apparatus used a 32 GHz source to investigate plasma turbulence in the AFOSR apparatus. The microwave power is incident on the plasma in the ordinary mode at a power level of approximately 25 milliwatts. The scattered power is observed for scattering angles from 20

to 160° in a plane normal to the magnetic field axis. The scattered microwaves were fed to a balanced mixer where they were detected with a crystal detector. The detected signal was then fed into either a spectrum analyzer or into an analog-to-digital data handling system for analysis and correlation with other signals, such as those from capacitive probes.

In these experiments, the electron number density ranged from 10^8 to 10^{10} particles per cubic centimeter, the magnetic induction ranged from B = 0.1 to 0.4 Tesla, the discharge current ranged up to 0.2 amperes, and the input power was as high as 600 watts. The angular dependence and scattering amplitudes were measured with the microwave scattering apparatus. The scattering data were correlated with plasma operating conditions and with data from capacitive probes which measured electrostatic turbulence. These scattering data permitted the measurement of absolute values of electron number density fluctuations, which ranged up to six percent of the RMS Density in these experiments - a very high value for the interior of magnetically contained plasmas. The frequency spectra density fluctuations of had a turbulent, power-law, continuous spectrum of fluctuations, with one or a few peaks superimposed on this background turbulence spectrum at frequencies characteristically a few 10's of kHz. Some of these spectra are shown among the data included in the paper presented at the Lausanne conference, which is included in Appendix E.

The peak at several 10's of KHz in the spectrum of density fluctuations in the AFOSR plasma was a function of the magnetic field strength and other plasma parameters. Unlike the functional dependence expected of rotating

spokes driven by E/B drift, the frequency of the rotating spoke was directly proportional to the magnetic induction, rather than inversely proportional to the magnetic induction, a new result. The frequency of the rotating spoke was also found to be a weak function of the electron number density, and a relatively weak function of the anode voltage.

Additional data, not presented at the Lausanne conference, was written up for presentation at the APS Plasma Physics Division meeting in Boston, Massachusetts, in late October, 1984. The abstract this paper is included in Appendix D.

The contracts currently active in the UTK Plasma Science Laboratory include an experimental contract to investigate characteristic phenomena in a modified Penning discharge (a Penning discharge in a axisymmetric mirror field), which is supported by the Office of Naval Research; and the present contract, supported by the AFOSR, to investigate characteristic phenomena in a classical Penning discharge (a Penning discharge operated in an axisymmetric, uniform magnetic field). These two parallel contracts, each supported at approxiamtely the same level of effort, and each supporting two graduate research assistants and one quarter of the Principal Investigator's time, provide a unique opportunity for a paired comparison of the phenomena occuring in these two Penning discharges.

Some results from the AFOSR experiment are incorporated in a paper presented at the International Conference on Plasma Physics held in Lausanne, Switzerland on June 27-July 3, 1984. This paper is included in Appendix E. It contains a paired comparison of the axial profiles and RF

emission of the AFOSR and ONR plasmas, generated, respectively, in a classical and a modified Penning discharge. It now appears that the existence of strong axial electric fields and high effective plasma resistivities is enhanced by the axial magnetic field gradients present in the modified Penning discharge characteristic of the ONR experiment. On the other hand, the production of monoenergetic ions of kilovolt potentials is enhanced by the uniform axial magnetic field associated with the AFOSR classical Penning discharge.

From approximately December, 1984, to March, 1985, the principal focus of our research activities was the absolute measurement of RF emission power from the classical Penning discharge plasma. To accomplish this, we used the calibrated, broadband antennas, described below, which were developed by Mr. Paul Spence, the Senior Research Assistant of the ONR contract, with ONR support. In developing these calibrated, broadband antennae, Mr. Spence had indispensible assistance and advice from Professor David Rosenberg, of the UTK Department of Electrical Engineering, some of whose time has been supported by the AFOSR contract during this fourth year.

These antennae have allowed us to do something which other plasma research groups have been able to do only very approximately if at all; measure the RF emission from a plasma in absolute units of watts per square centimeter in the far field, while receiving the RF emissions over a broad range of frequencies (in our case from 100 MHz to 1.2 GHz) with broad-band antennas with a nearly flat frequency response. Thus, when we look at a

emission power spectrum from the classical Penning discharge, we can be assured that, over the frequency range just quoted, we are looking at the characteristics of the plasma itself, and not at the frequency response or response pattern of our antenna. Also, when we integrate the total power under the frequency spectrum so observed, we have a reasonable assurance that we are measuring the total power emitted by the plasma. This allows us to make measurements of emitted power as a function of plasma number density, magnetic field, operating conditions, and, most important for Air Force applications, the electrical efficiency in terms of the total RF output power divided by the electrical power required to energize the discharge.

During this fourth year, Prof. Igor Alexeff and I continued our collaboration on the theory of growing waves and electromagnetic emission from two oppositely directed electron beams in a cold background plasma. This collaborative work has extended our discovery papers on the interpenetrating beam or geometric mean emission frequency, which were written up in references 1 and 2. We presented a paper on our theoretical results at the 26th Annual Meeting of the APS Division of Plasma Physics, which was held in Boston, Massachusetts from October 29 through November 2, 1984.

In that paper, we presented a generalization of previous theoretical work to the case of two nonrelativistic, oppositely directed interpenetrating electron beams of unequal density, interacting with a cold background plasma. These conditions can be reduced to a sixth order cold plasma dispersion relation with growing and damped solutions. In the case of two beams, each half of the total

electron density, interacting with cold ions, we recovered our previous result, quoted in references 1 and 2. These previous results predicted growing waves near the geometric mean of the electron and ion plasma frequency. When the beams are much less dense than the cold electron background density, the growing waves are near the electron plasma frequency of the cold electron population. The maximum growth rates were found to be not at the beam electron plasma frequency or at the upper or lower hybrid frequency. The frequency of an oscillator based on this instability may be tuned by adjusting the relative intensity of the two beams as well as the beam density relative to the background plasma. The abstract of the paper presented at the APS meeting on October 29, 1984 is included in Appendix D.

During this fourth year, we also began a new theoretical initiative in collisional and transit time magnetic pumping, because of its close relation to our work on plasma turbulence and anomalous collision frequencies in turbulent plasmas. The general subject of collisional and transit time magnetic pumping was initially cultivated under national security wraps during the mid 1950's, when the entire fusion program was classified, and various RF-based schemes were being considered for plasma heating. Upon declassification in 1958, a fundamental survey paper on RF heating by Burger et al. (Ref. 6) was published, which summarized, among other things, the theoretical results on collisional and transit time magnetic pumping which had been derived up to mid 1958. This paper contained an outline of the theory of collisional and transit time magnetic pumping, which was not followed up in the literature with further publications. The very brief

discussion in that paper adopted a very abbreviated and telegraphic style, in which the basic equations were written down, followed by the result, with no intermediate steps. The only help to the reader was an off-hand remark that the result was obtained by application of Floquet theory. Floquet theory is a method used in celestial mechanics and applied mathematics to deal with differential equations with periodic coefficients. Apparently collisional and transit time magnetic pumping did not appear attractive relative to other plasma heating schemes of the time, such as ion cyclotron resonance heating or Alfven wave heating. No further theoretical or experimental work of any significance appears to have been done from the publication of that paper until the present.

Collisional and transit time magnetic pumping are accomplished by taking an axisymmetric, cylindrical plasma, wrapping an exciting coil around the plasma over a length L, and then exciting the coil with a low frequency which perturbs the background confining axial magnetic field in the plasma. If the magnetic moment, $m\ v^2_{\perp}/B$, remains constant, then the increase or decrease of the axial magnetic field, forced at the driving frequency, will change the perpendicular components of the ion and electron energy. If collisions occur, some of the perpendicular energy fed in by this magnetic pumping will be transfered to the parallel direction, thus heating the plasma.

The classical method of collisional or transit time magnetic pumping, which was described by Burger, et al. (Ref. 6), as well as Rose and Clark, Miyamoto, and other plasma physics textbooks, contemplated putting a sinusoidal signal on the exciting coil, which alternately raises and lowers the

axial magnetic field above and below the constant, dc axial field existing outside the pumping coil.

It occured to me that this arrangement of magnetic pumping was inefficient, because one loses almost as much perpendicular energy in the negative half of the sinusoidal excitation as one gains in the positive half of the cycle. Indeed, the original theory of Berger, et al. was somewhat discouraging as to the heating rates and heating effectiveness possible using this form of magnetic pumping. I thought that if one used a time varying excitation such that the currents in the exciting coil flowed only in a direction to enhance the background magnetic field, then the perpendicular ion and electron energy could only increase above its equipartition value outside the pumping region. Collisions would then be far more effective in transfering energy from the perpendicular components. I suggested this as a possible Ph.D. thesis problem to Mr. Mounir Laroussi, who is the Senior Research Assistant for the AFOSR contract. Mr. Laroussi started out by reproducing the many missing steps in the original article by Burger, et al., to make sure that we knew how the authors got from their basic equations to their result. This has been done, and appears in the Interim Scientific Report for the fourth year, and in the first part of the archival SSST Symposium paper in Appendix E.

Summary of Technical Results, Final Year

By the beginning of the final contract year, which spanned the period from March 15, 1985, to March 14, 1986, the vacuum system of the classical

Penning discharge had been upgraded by the installation of a new set of more reliable ion gauges which were capable of automatic ranging; the installation of a Veeco mass spectrometer to monitor the impurities in the vacuum system and allow leak detection; and the installation and operation of a freon-cooled cold trap which reduced the base pressure to the low 10^{-6} torr range. These additions and improvements, which had been made over the previous twelve months, did not change our experimental results in any way, but made it much easier to obtain reproducible, high quality results more rapidly than was possible with the older vacuum technology previously in use.

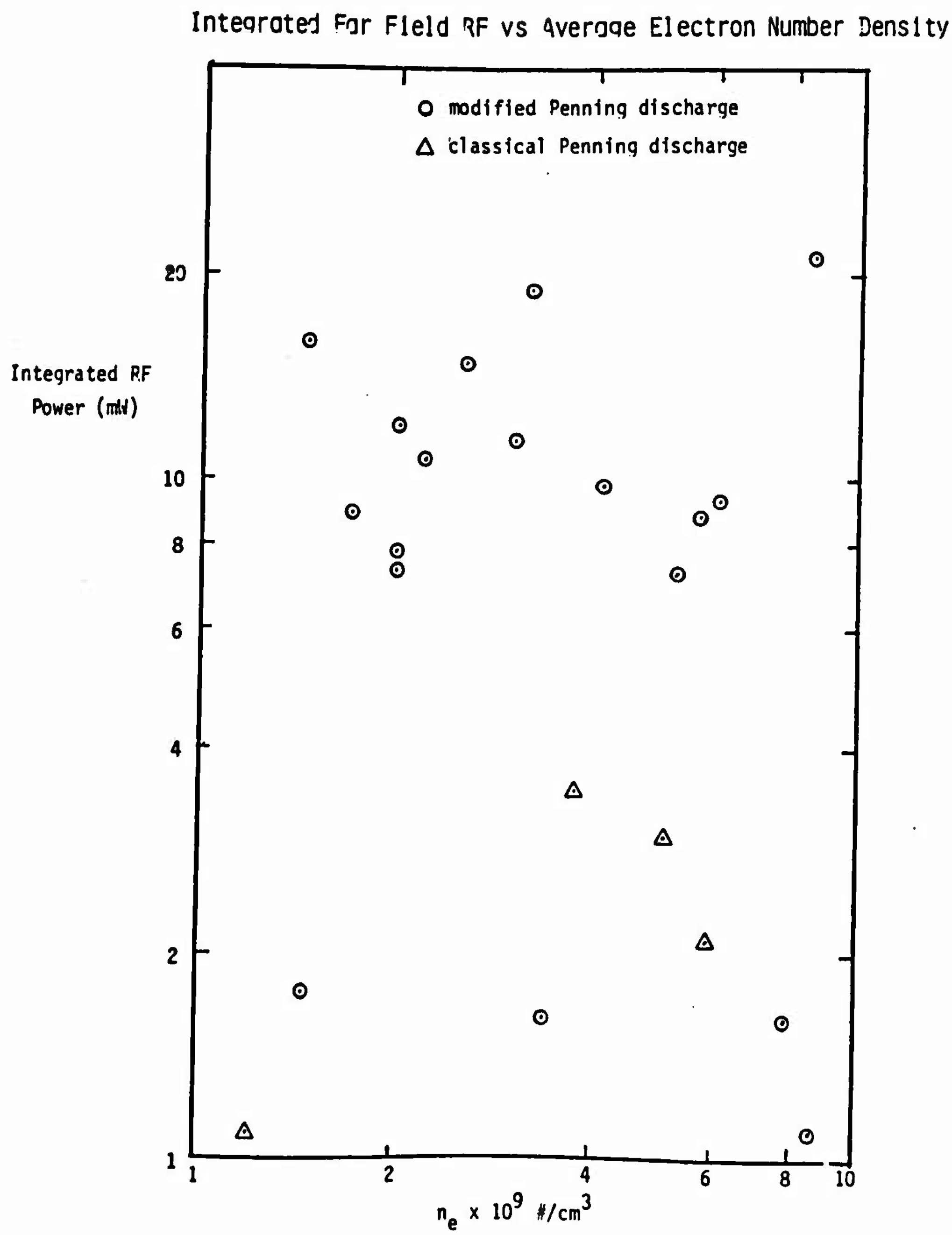
Also during this final year of the contract, the low frequency and microwave network analyzers, and other equipment purchased with the DoD-URIP equipment grant, were ordered, delivered, and applied to the data taking process with some very gratifying results, which were presented at the November, 1985 APS Plasma Physics Division meeting; at the IEEE Plasma Science meeting held in Pittsburg, PA in 1985, and at the 1986 IEEE meeting in Saskatoon, Canada, in 1986.

The network analyzers were used to measure absolute RF power measurements for the near and far field from the classical Penning discharge. The emission spectra observed cover the frequency range from 0 to 1 GHz. The measured power has been plotted against the electron number density calculated from Langmuir probe measurements in Figure 8. The efficiency, defined as the radiated RF power, divided by the dc input power to the

discharge, was also measured as a function of the input power and is plotted in Figure 9. These efficiency measurements were disappointing. The efficiency of power generation in the frequency band from 0 to 1 GHz was on the order of 0.1%, and tended to decrease with increasing power input to the discharge. The power radiated from the discharge increased no faster than linearly with the electron number density of the discharge. Even at number densities above 4×10^9 electrons per cubic centimeter, the radiated power declined with increasing electron number density, perhaps as a result of a self-shielding effect.

During a series of measurements, two types of waves were observed. The first type was in the frequency range from 10 to 100 KHz. The wave frequency was independent of the magnetic field, but a function of the neutral number density. This appears to be an example of the continuity equation oscillation, previously observed and reported by the Principal Investigator prior to 1970. The continuity equation frequency observed had the theoretically predicted square root dependence on the product of the neutral number density and the ion number density. The phase spectrum of this oscillation observed with two probes, showed no phase shift both azimuthally and axially, implying that the entire plasma was oscillating in unison with a single phase and frequency, again characteristic of the continuity equation oscillation.

The second type of wave observed in these experiments was seen over the frequency range from 200 to 500 KHz. This frequency was proportional to 1/B, and directly proportional to the anode voltage. These oscillations are due to the E/B cross field drift instability. Radial electric fields up to 1 kilovolt per



Integrated Far Field RF vs Average Electron Number Density
modified Penning discharge
classical Penning discharge
Integrated RF Power (mW)
20
10
8
6
4
2
1
1
2
4
6
8
10
$n_e \times 10^9$ #/cm^3

FIGURE 8

Radiating Efficiency vs Average Electron Number Density

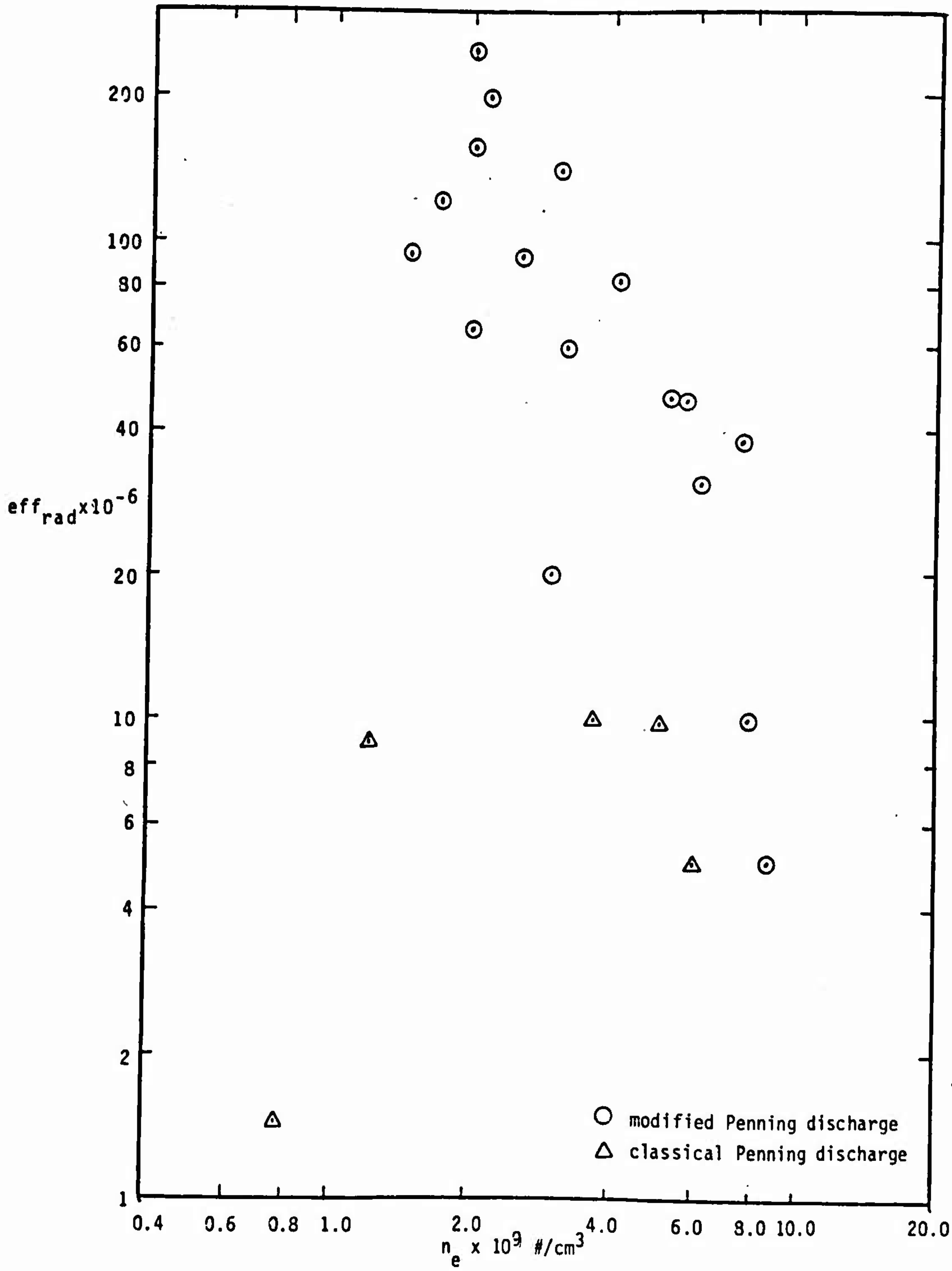


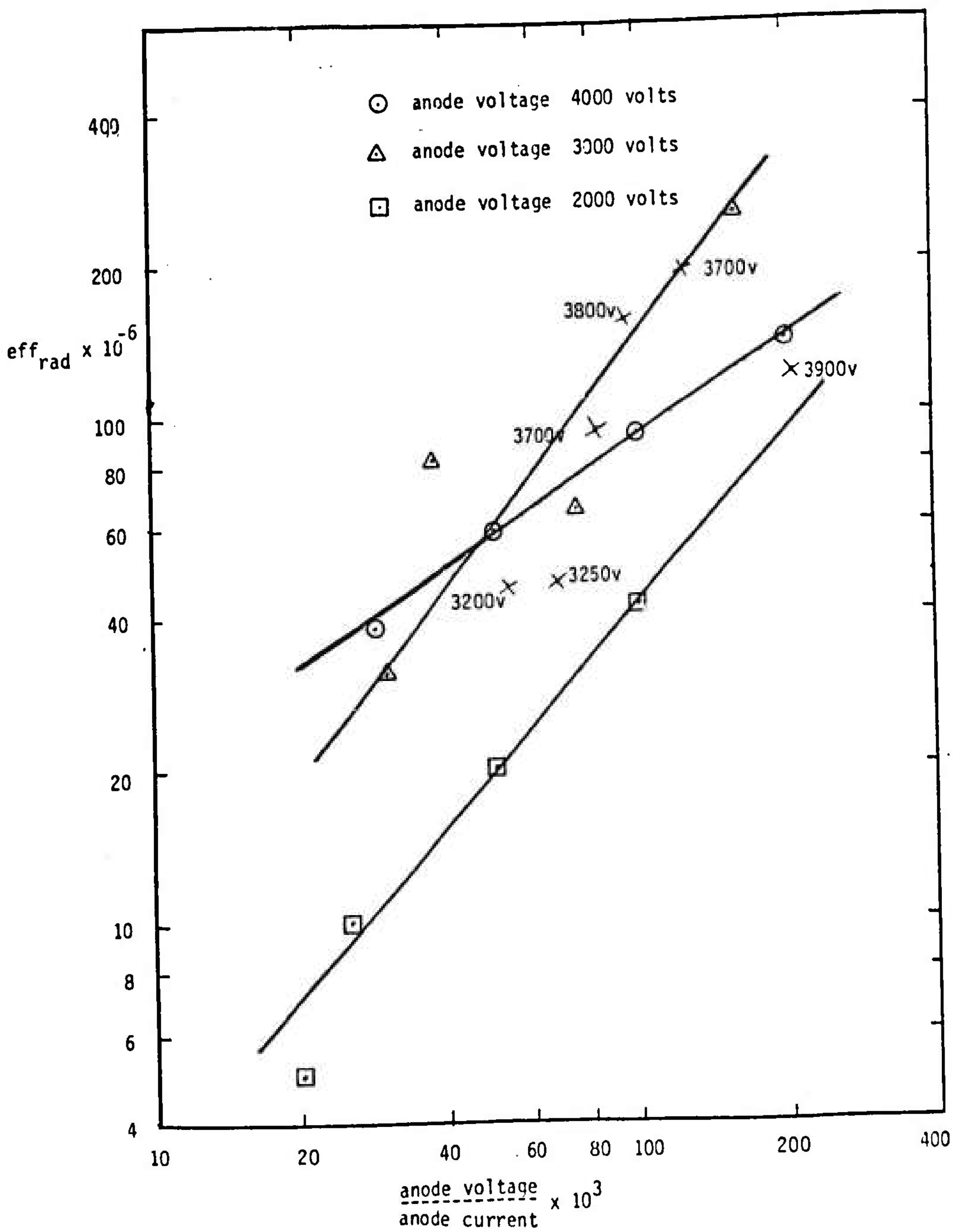
FIGURE 9

centimeter have been observed. The group velocities of these waves have been calculated and are on the order of 20 kilometers per second.

Our new network analyzers, combined with low noise amplifiers and careful attention to experimental technique, allowed us to observe turbulent spectra of electrostatic potential fluctuations in this discharge over a dynamic range which, in some cases, exceeded 70 decibels from frequencies of 1 kilohertz up to 10 MHz.

During the Summer and Fall of 1985, a series of paired comparison measurements were made on the classical Penning discharge, and the modified Penning discharge operated for our ONR contract in the UTK Plasma Science Laboratory. The two Penning discharges were operated over a range of number densities between 1.0 and 10 x 10^9 electrons per cubic centimeter, while the far-field radiation was observed with a calibrated, broadband antenna which measured the emitted radiation in the bandwidth from 100 to 1000 MHz. It was found that the integrated RF power from the modified Penning discharge, operated in a mirror magnetic field, was at least a factor of five times higher than the RF power emitted from the classical Penning discharge. These data are shown in Figure 8. The radiation efficiency is defined as the integrated RF power of an isotropic emitter over 4π steradians, divided by the dc electrical input power to the discharge. This radiation efficiency is plotted as a function of the average electron number density for the classical and modified Penning discharges on Figure 9. Here again, it is evident that the modified Penning discharge generates broadband radiation much more efficiently than the classical Penning discharge of the

Radiating Efficiency vs $\frac{\text{Anode Voltage}}{\text{Anode Current}}$



Air Force experiment. The difference in radiation efficiency is characteristically an order of magnitude. The efficiency of the modified Penning discharge decreases with increasing number density, perhaps as a result of a self-shielding effect of the plasma. The magnitude of the radiation efficiencies for this data set are even smaller than earlier data, taken at higher anode voltages. The fraction of the dc input power radiated as RF varies between one part in 10^4, and one part in 10^5. On Figure 10 is shown the radiation efficiency as a function of the effective dc resistance of the discharge. This is obtained by dividing the anode voltage by the anode current, and is related to the anomalous resistivity in the bulk of the plasma.

These data were somewhat discouraging, in that they seem to indicate that the steady state version of the classical Penning discharge is not very efficient in converting dc electrical power into broadband radiation. The data on Figure 8 indicate that the integrated power emitted from the classical Penning discharge is on the order of 1 to 4 milliwatts, when several hundred watts of dc power are consumed by the discharge. These low efficiencies may result from the RF generation mechanism being inherently inefficient, or it may result from relatively large fixed losses in the classical Penning discharge which are necessary to produce the volume ionization to sustain the plasma. If the latter is the case, a pulsed version of the classical Penning discharge, operating at much higher powers, might be much more efficient. However, it appears that the modified Penning discharge, with its axial magnetic field gradients and higher axial electric fields, is a more effective

configuration for generating broadband RF power than the classical Penning discharge used in the Air Force experimental program.

During this final year of the contract, theoretical investigations aimed at studying collisional magnetic pumping were able not only to reproduce the earlier results of Burger et al., but also to generalize the collisional magnetic pumping theory presented by Burger and his colleagues in the 1950's to a magnetic field perturbation of arbitrary waveform. An important result of this generalized theory of collisional magnetic pumping is that a sawtooth waveform of magnetic perturbation is capable of providing first order heating, proportional to the magnitude of the magnetic perturbation. The first-order heating rate possible with a sawtooth waveform is approximately a factor of 500 larger than the second order collisional magnetic pumping achieved with a sinusoidal waveform which is alternately above and below the prevailing, unperturbed magnetic field. This occurs because when the sawtooth waveform is used, the perpendicular energy is always above the value outside the exciter coil, and the net stochastic energy flow is unidirectional into the parallel energy components of the plasma. This aspect of the theory was written up in a paper for the Southeastern Symposium on Systems Theory, held in Knoxville, Tennessee in April, 1986. This paper is included in Appendix E, pages E-6 through E-10.

Other progress during this report period was made by Mr. John Crowley, a master's student in Electrical Engineering who joined the UTK Plasma Science Laboratory in June of 1985, and expects to receive his Master's degree in the summer of 1986. Mr. Crowley is developing a two-

channel spectrum analyzer system with instrumental interchannel noise coupling of less than 50 db. The approach is to use a narrow band filter linked to the Hewlett Packard low frequency network analyzer operating in a spectrum analyzer mode. Mr. Crowley has developed a narrow band filter with a movable center frequency, which sweeps in synchronization with the spectrum analyzer, and only allows frequency components into the analyzer, at the frequency it is analyzing at the moment.

With this two channel analyzer, we will be able to detect mode coupling due to nonlinear effects in the plasma, and be confident (at least down to the 50 db limit of this new instrument) that any nonlinear mode coupling between frequencies which we observe in the plasma turbulence spectrum is due to the plasma, and not to inter-channel, nonlinear coupling within the experimental apparatus itself. This problem of nonlinear coupling in the instrumentation is one which has not previously been addressed in plasma research, and we expect that the uncontaminated nonlinear mode coupling data which this will allow us to take will provide some interesting insights into the energy cascading process in turbulent plasma energy flows.

Utility of Research to the Air Force

The basic research on steady state electric field dominated plasmas performed under this contract has potential relevance to several areas of Air Force concern. These include the production of broad-band RF emissions suitable for jamming military communications; the enhancement of plasma

turbulence, accompanied by plasma heating; the heating of plasmas by collisional magnetic pumping and/or turbulent energy cascading; the simulation in a steady-state, laboratory plasma of RF emission and turbulence related phenomena which may occur on a microsecond time scale in intense particle beam sources and intense RF sources of weapons interest; and the observation of anomalous plasma resistivity, which should allow much higher power densities to be developed than would be possible in plasmas in which the resistivity is dominated by binary particle collisons (Spitzer or Lorentzian resistivity). More information about these potential areas of application is given below:

Efficient Generation of Microwave Power

In Penning discharges, the emitting electrons and ions are trapped by a combination of electrostatic and magnetic trapping (Refs. 3, 4). The average particle lifetime is much longer than a single transit time, in contrast to travelling wave tubes where the emitting electrons are not trapped, and pass once through the interaction region in a single transit time. The trapping of electrons and ions in the emitting volume may lead to much higher efficiencies for RF emission than are possible in once-through devices like traveling wave tubes.

High efficiencies, which one might expect for the above reasons, have not been observed thus far in our experiment. The ratios of microwave power output to dc input power to the discharge are typically from 10^{-4} to 1% at dc input power levels on the order of several hundred watts. It may be that the

interpenetrating beam mechanism responsible for much of the RF radiation from these plasmas may be a minor, parasitic phenomenon, with the power balance of the discharge dominated under all conditions of operation by volume ionization; line emission; and the production of energetic ions, at energies comparable to the anode potential, which are lost to the cathode surface. It also may be the case that the power consumption mechanisms just mentioned may represent fixed losses, which will become less significant as the operating power levels or number density of the discharge are increased. Although the data obtained under this contract give us little reason for encouragement, we have not given up on the possibility of efficient generation of microwave power using the classical Penning discharge, and hope to get some data on high number density, high power pulsed Penning discharges as a part of our future research program at the UTK Plasma Science Laboratory.

Broadband Microwave Power Generation

Experimental data show that RF emissions occur over a very broad frequency band, from below 0. 6 MHz to frequencies as high as 2 GHz. Under the appropriate conditions, the emissions are capable of jamming AM/FM reception in Ferris Hall, the building in which the UTK Plasma Science Laboratory is located. When the plasma operating conditions are just right, the Rf emission is a virtually flat white noise spectrum over frequencies up to at least 1 GHz. The physical processes responsible for such a high degree of non-linear mode coupling and for such broad-band RF emission are not yet understood, but are clearly related to the geometric mean emission frequency

and accompanying non-linear mode coupling, which give rise to RF emission at the harmonics of this frequency. This broad-band emission has the potential for development into a useful jamming tool, especially if the emitter were operated on a high power or pulsed basis. The efficiency with which this broad-band emission can be generated has been measured at levels from 0.1 to 1.0 percent, under grossly non-optimized operating conditions.

The available experimental data suggest that efficient production of broadband radiation probably is not possible under the conditions under which we have operated our classical Penning discharge in the laboratory. The paired comparison between the classical and modified Penning discharges indicates strongly that the axial magnetic field gradients of the modified Penning discharge increase the efficiency of broadband RF power generation by at least a factor of 10. Future work on developing efficient, broadband RF emission from Penning discharges should therefore use the modified Penning discharge configuration, in which the Penning discharge is operated in a magnetic mirror geometry with axial magnetic field gradients. In addition, pulsed operation at high power levels and higher electron number densities may also improve the efficiency of this broadband RF emission.

Processes in High-Power, Pulsed Plasmas

The classical and modified Penning discharges may simulate physical processes that occur in intense particle beam sources and high power microwave sources, but do so in the steady state, and in plasmas of sufficiently low density that conventional diagnostic instruments can be used to measure

the characteristics of the plasma and of the resulting RF radiation. In some cases, the electric and magnetic geometry of the classical Penning discharge is similar to that of particle beam sources and/or high power microwave sources. In our Penning discharges, relativistic effects are not important, as they would be in intense relativistic electron beam devices. Penning discharges may, however, provide useful information about physical processes in non-relativistic proton beam sources and/or high power microwave sources, in which RF emission at the electron cyclotron frequency is not too important.

Some of our results which may be of interest to those engaged in research on relativistic or high power pulsed microwave and particle sources are the importance of the two interpenetrating beam plasma oscillation; the importance of E/B drift waves in the plasma dynamics; the observation in this plasma of the continuity equation oscillation; observation of the diocotron instability; and the production of kilovolt ions with a broad energy distribution, sometimes Maxwellian. These findings may be of interest for directed energy weapons, or to other technologies that generate ion or electron beams.

High Power Density Plasma Generation

The penetration of electric field dominated plasmas by strong radial and axial electric fields is characteristic of Penning discharges. These electric fields allow the radiating ion and electron populations to be coupled directly to an external dc power supply, thus imparting energy to the radiating species in the same volume in which the RF emission orginates.Our research program

has demonstrated the existence of axial electric fields of several hundreds of volts per centimeter, and turbulence-induced anomalous resistivities of many orders of magnitude above that of binary collisional processes. This research may lead not only to mechanisms for creating plasmas at a very high steady state power density, but also to RF emitters more efficient than single-pass-through devices like the traveling wave tube.

Plasma Heating by Collisional Magnetic Pumping

Our research program of the last year and a half of this five year period was able to show theoretically that first-order plasma heating by collisional magnetic pumping should be a very effective process, approximately 500 times more effective than the second order plasma heating initially proposed by Burger et al. Collisional magnetic pumping may prove to be a very efficient way to heat partially ionized plasmas of interest in high power lasers, directed energy weapons, or other applications in which rapid heating of plasmas at power input levels in the kilowatt or megawatt ranges are desired for military applications. Our theoretical demonstration of an effective means of collisional magnetic pumping should provide a new and more efficient alternative to the heating of partially ionized plasmas for a wide range of high power density applications of interest to the Air Force.

RESULTS OF OTHER CONTRACT PROGRAMS

In addition to the program of experimental research, the results of which are described above, this contract served as a vehicle to accomplish several additional objectives which were important to us here at the University of Tennessee, Knoxville, and which would not have been possible without the support of the Air Force Office of Scientific Research.

Development of the UTK Plasma Science Laboratory

Although development of the UTK Plasma Science Laboratory was not a major goal of this research contract, AFOSR support has played important role in elevating the research effort in experimental plasma physics at the University of Tennessee from a low level to a "critical mass" of student and faculty research effort in the areas of electric field dominated plasmas, plasma turbulence, and the interaction of RF radiation with high temperature plasmas. Part of the physical impact of Air Force support may be seen in Figures 1 and 2, which show the UTK Plasma Science Laboratory before and after building up of the classical Penning discharge, on which the research in this report was conducted. In addition to providing the manpower required to set up and operate this steady-state plasma research facility, the Air Office of Scientific Research has, through the DoD-University Research Instrumentation Program, provided an additional $233,000 for state-of-the-art equipment which has benefited not only the AFOSR research contract in

its last year, but also has had a major impact on the ONR and other contract research in the UTK Plasma Science Laboratory. The availability of training on this state-of-the-art equipment has not only attracted well qualified research assistants, but also regular graduate and upper division undergraduate students who have worked for us free, for the experience of working with this state-of-the-art equipment. Support by the Air Force Office of Scientific research was instrumental in making the UTK Plasma Science Laboratory, over the past six years, into an important center in the southeastern United States for the experimental investigation of plasmas, and the training of students in plasma science and related disciplines.

Support of Graduate Study and Research at UTK

Prior to 1980, there was no externally supported graduate study and research in experimental plasma physics on the UTK campus. With Air Force and ONR support, the UTK Plasma Science Laboratory now offers students at both the undergraduate and graduate level hands-on training in experimental plasma physics research with state-of-the-art equipment, using diagnostic methods which are at the forefront of university and national lab plasma physics research. The contract summarized in this report supported faculty and graduate student assistants at the levels indicated in Table 2. This contract provided 9 man-years of training at the graduate level, and an additional three man-years of training to undergraduates who were hired with "surplus" funds during the first four years of the contract, or who were

TABLE 2

CONTRACT STAFFING HISTORY

HIGHEST DEGREE AT UTK	DEGREE RESEARCH DONE IN UTK PLASMA LAB	WORKING AT	CURRENT STATUS	YEAR	CONTRACT DURATION	PERSONNEL	STATUS	DURATION OF SERVICE, MONTHS	FRACTION OF TIME WHILE IN SERVICE
—	—	—	—	1	3/15/81-3/14/82	J. Reece Roth	Faculty, P. I.	12	0.25
M.S.	No	UTSI	GRA			Robert L. Pastel	GRA	11	0.50
B.S.	—	TRW, MIT	—			Roger A. Richardson	Summer RA	3	0.50
—	—	—	—	2	3/15/82-3/14/83	J. Reece Roth	Faculty P. I.	12	0.25
M.S.	No	UTSI	GRA			Robert L. Pastel	GRA	12	0.50
B.S.	No	Univ. of Illinois	GRA			Gregory J. Hutchens	UGRA	6	0.50
M.S (Ph.D.)	Yes	UTK Plasma Lab	GRA			Paul D. Spence	GRA	6	0.50
—	—	—	—	3	3/15/83-3/14/84	J. Reece Roth	Faculty, P. I.	12	0.25
M.S.	No	UTSI	GRA			Robert L. Pastel	GRA	3	0.50
M.S (Ph.D.)	No	Spinlab	Part-Time Ph.D. Student			Peyman Dehkordi	GRA	3	0.50
M.S.	No	UTK	GTA			Feroz Alam	GRA	6	0.50
M.S. (Ph.D.)	Yes	ORNL	Part-Time Ph.D. Student			Larry Baylor	Student-unpaid	6	0.25
M.S (Ph.D.)	Yes	UTK Plasma Lab	GRA			Mounir Laroussi	GRA	6	0.50
M.S.	Yes	GE Aircraft Engine Plant, Cincinatti, Ohio	Employed			Saeid Shariati	GRA	6	0.50
—	—	—	—	4	3/15/84-3/14/85	J. Reece Roth	Faculty, P. I.	12	0.25
—	—	—	—			David Rosenberg	Faculty	9	0.10
M.S. (Ph.D)	No	Spinlab	Part-Time Ph.D. Student			Peyman Dehkordi	GRA	3	0.50
M.S.	No	UTK	GTA			Feroz Alam	GRA	3	0.50
M.S. (Ph.D.)	Yes	ORNL	Part-Time Ph.D. Student			Larry Baylor	Student-unpaid	6	0.25
(Ph.D.)	No	UTK	GTA			John Mannone	GRA	6	0.50
(Ph.D.)	Yes	UTK Plasma Lab	GRA			Mounir Laroussi	GRA	12	0.50
—	—	—	—	5	3/15/85-3/14/86	J. Reece Roth	Faculty, P. I.	12	0.25
—	—	—	—			David Rosenberg	Faculty	12	0.20
(Ph.D.)	Yes	UTK Plasma Lab	GRA			Mounir Laroussi	GRA	12	0.50
(Ph.D.)	No	UTK	GTA			John Mannone	GRA	3	0.50
(M.S.)	Yes	UTK Plasma Lab	GTA			John E. Crowley	GRA	9	0.50
(B.S.)	No	Various	B.S.			UG Research Assistants (7 ea)	UGRA	3 ea	0.50 ea

part of our undergraduate research assistant pilot program in the summer of 1985.

This five year contract from AFOSR not only has made possible the creation of a critical mass of students and faculty at the University of Tennessee, Knoxville, but it has supported in their entirety two master's theses in the UTK Plasma Laboratory, by Larry R. Baylor and Saeid Shariati, and it has supported the bulk of a masters thesis by John E. Crowley (Mr. Crowley will finish up his Master's thesis, entirely under AFOSR support, in June 1986, approximately four months after the termination of this five year contract). This contract also has supported the bulk of a Ph.D. Thesis on collisional magnetic pumping by Mr. Mounir Laroussi, who expects to get his Ph.D. in June, 1987 entirely under AFOSR sponsorship.

The UTK Plasma Science Laboratory has graduated three Master of Science in Electrical Engineering students in the past three years who have completed their Master's theses while working as research assistants in the Plasma Lab. These students include Mr. Larry R. Baylor, who obtained his Master of Science in Electrical Engineering in June, 1984, and is now employed in the Instrumentation Division of the Oak Ridge National Laboratory. Mr. Saeid Shariati completed his Master's degree in Electrical Engineering in March, 1985, and is employed at the Aircraft Engine Division of General Electric in Cincinatti, Ohio. Finally, Mr. Peyman Dehkordi obtained his Master's degree in Electrical Engineering, and is now employed by Spinlab, Inc., of Knoxville, Tennessee, where he is applying his

instrumentation skills to the development of process control equipment for the spinning and weaving industry.

Support of Computational Physics

During the final year of this five year contract, it served as a vehicle for a collaborative research effort with Dr. Robert J. Barker of AFOSR, our technical program monitor. Our contract was used to purchase approximately $15,000 worth of hardware needed for a part-time computational physics effort by Dr. Barker at the Bolling Air Force Base in Washington, where he is headquartered. This hardware consisted of an IBM AT computer, disk drives, a plotter, and other accessories needed to link this system to other mainframe computers available to Dr. Barker in Washington, and to conduct computational physics investigations.

Support of AFOSR Undergraduate Research Assistantship Program

In the Spring of 1985, during the final year of this contract, the UTK Plasma Science Laboratory was selected by the AFOSR to run a pilot program in which undergraduate engineering students were hired as research assistants affiliated with the ongoing Air Force contracts at the University. During the Summer of 1985, the UTK Plasma Science Laboratory had six students in this pilot program, two working under the direction of Professor Igor Alexeff, and four under the direction of Professor J. Reece Roth. This

program was set up to acquaint bright undergraduate engineering students with the advantages of graduate level education and research; to improve their skills; and to acquaint them with Air Force Research. The program was conceived within the AFOSR by Dr. Robert Barker, and put in place as a pilot program at only three institutions; UTK, New York Polytechnic University, and the University of Miami at Coral Gables.

The program was very successful at UTK. Our students were each assigned, in addition to occasional gofering activities, a specific project to be completed by the end of the summer. They were asked to sign up for three credit hours of EE 4910, Senior Project Lab, and they were graded for credit on the documented write-up of their project at the end of the summer. In effect, they did a bachelor's thesis, as well as contributing their documented projects to our AFOSR and ONR research programs. These students met with the rest of the Plasma Science Laboratory staff for a weekly research conference during the summer, and interacted with the senior graduate research assistants as well as the Principal Investigator. The success of this program during the Summer of 1985 has been such that a continuation of this program is planned for the next three years, 1986-88.

INTERACTIONS WITH OTHER RESEARCH EFFORTS

Publications

The progress made and research results obtained under this contract have been systematically documented in the four Interim Scientific Reports listed in Table 1, in the conference presentations described in the next section of this report, in archival papers presented at international scientific meetings in 1982 and 1984, as archival conference proceedings, and as final reports of completed work in the form of masters or Ph.D theses which acknowledge Air Force support, and are available through University Microfilms.

Copies of the Interim Scientific Reports on this contract are already in the hands of the AFOSR; copies of the archival scientific papers presented at the International Conference on Plasma Physics in 1982 and 1984 are included in Appendix E of this report. Abstracts, tables of contents, and the title page from the interim scientific reports are included in Appendix G of this report, and the abstracts, tables of contents, and titl ges of the theses already published and supported by this contract are listed i Appendix F .

Conference Presentations

In addition to the archival and full-length reports of completed work described in the previous section, and documented in Appendices E through G

of this report, there were numerous conference presentations listed in Appendix D, in which progress on this AFOSR contract was reported to our professional peers. We have made it a practice to regularly present progress reports on the activities of this contract at the IEEE International Conference on Plasma Science, held on May of each year, and also at the annual meeting of the American Physical Society's Plasma Physics Division, usually held in early November of each year. Most of these conference presentations were in poster format, and were progress reports covering the previous six months of activity under this contract. The poster and/or transparency materials for these presentations were contained in the four Interim Scientific Reports listed in Table 1.

Presentation of the work done under this contract at these conferences allowed us to interact with other investigators from such Air Force related laboratories as the Edwards Air Force Base, The Kirtland Air Force Base, The Wright-Patterson Air Force Base, the Harry Diamond Laboratories, the Naval Research Laboratory, as well as many other DoE and DoD Principal Investigators of university contracts, at such universities as the University of Texas at Austin, the Polytechnic University of New York, The University of Miami at Coral Gables, Texas Tech University, and others.

Collaboration with the University of Texas, Austin

The software required to obtain auto-and cross-power spectra and other statistical properties of plasma fluctuations was originally developed by

Professor Edward J. Powers of the University of Texas at Austin and his students. This computer program has been made available to us by Prof. Powers, and has been modified and entered into our mainframe computers at UTK. Professor Powers' program is based on a fast Fourier transform of the incoming time series supplied by the analog-to-digital data handling system, and produces auto power spectra, cross power spectra, phase spectra, coherence spectra, transport spectra, and a plot of the time series itself for the 3 simultaneous input channels of information. This software also has been used to obtain the fluctuation data which we presented at meetings. Mr. Paul Spence from the UTK Plasma Science Laboratory traveled to the University of Texas at Austin in March, 1985, and was given additional software programs for bispectral analysis of digital time series, and other programs which will be extremely useful in studying fluctuations and turbulence in plasmas.

Collaboration with Dr. Robert J. Barker

A recent initiative during the final year of this contract, was arrangement for a collaborative research effort with Dr. Robert J. Barker of AFOSR, our technical program monitor. Dr. Barker's expertise in computational physics is potentially of great value to our research program, since he may be able to tie the two interpenetrating beam instability theory which has been developed in the linearized limit by Profs. Alexeff and Roth, to the actual non-linear manifestation of this instability which we observed in

the laboratory. Other opportunities for collaboration in computational physics including estimating the relevance of our experimental measurements with steady-state, non relativistic plasmas, to plasmas of interest for weapons applications which are pulsed and relativistic; simulation of the bunching (diocotron) instability in the Penning discharge; or simulation of the heating process using collisional magnetic pumping.

DOD Contracts at the UTK Plasma Science Laboratory

During the period of this report, the UTK Plasma Science Laboratory was supported by three DOD contracts. The first research contract to be awarded was ONR-N00014-80-C-0063 (Roth). Dr. Charles W. Roberson, Technical Monitor, which was granted on January 1, 1980, and has been extended through September 30, 1987. This contract is concerned with exploratory experimental investigations of the physical processes in electric field dominated plasmas generated in the steady state by a modified Penning discharge located in an axisymmetric magnetic mirror geometry. These investigations are focusing on RF emissions from the plasma, non-linear mode coupling of plasma fluctuations, axial electric field profiles, and other phenomena which may be related to, or have analogs in, the magnetosphere.

The second contract to be awarded to the UTK Plasma Science Laboratory was AFOSR-81-0093 (Roth), which started on March 15, 1981, and terminated on March 14, 1986. This contract was concerned with the investigation of physical processes in an electric field dominated plasma

produced by steady-state operation of a classical Penning discharge with an approximately uniform axial magnetic field profile. The phenomena of particular interest in this investigation were anomalous plasma resistivity, axial electric field profiles, plasma turbulence, turbulent heating of ions, non-linear phenomena relating to energy dissipation in the plasma, and plasma heating by collisional magnetic pumping.

Professor Igor Alexeff of the UTK Department of Electrical Engineering has held AFOSR contract 82-0045, which terminated on March 14, 1986. This contract covered the development of a submillimeter microwave emitter based on the Orbitron configuration. Prof. Alexeff holds a US patent on this device, and under AFOSR sponsorship, has analyzed its operation and instabilities theoretically, while pursuing an experimental program which has achieved steady state operation, and generated wavelengths down to 0.3 millimeters. The Orbitron configuration has attracted interest at the Naval Research Laboratory, at the Hughes Research Laboratories, and other places where advanced research on microwave emitters is conducted.

Comparison of Classical and Modified Penning Discharges

The research contracts with the AFOSR and Office of Naval Research have been operated in parallel, and have shared much of the same computer software, diagnostic equipment, electronic test equipment, power supplies, microwave equipment, and other facilities of the UTK Plasma Science Laboratory. Nonetheless, each contract has had a different set of goals and

objectives, with the exploratory research for ONR being conducted on a modified Penning discharge, a Penning discharge operated in a magnetic mirror field with a 5:1 variation of magnetic field along the axis, and the AFOSR exploratory research conducted in a classical Penning discharge, with a uniform magnetic field along its axis.

This conjunction of two different kinds of Penning discharge operating in the steady-state, and in the same laboratory, made possible a paired comparison of the properties of these two forms of Penning discharge. This comparison was explored in the archival papers included in Appendix E, which were presented at the 1982 and 1984 International Conferences on Plasma Physics.

These paired comparison experiments on the two types of discharge established that axial magnetic field gradients greatly enhanced the axial electric fields observed, and it also established that the level of RF emission was from a factor of 10 to a factor of 100 greater from the modified Penning discharge than it is from the classical Penning discharge supported by the Air Force contract. Both Penning discharge plasmas had approximately the same type of current-voltage curve, with hysteresis and discontinuous jumps on the current-voltage diagram. Both functioned in two distinct modes of operation, and they tended to operate over the same general range of electron and neutral number densities. Other points of similarity and difference are discussed in the papers included in Appendices D and E.

Other Presentations, Visits, and Reviews

During the five year history of this contract, the Principal Investigator has interacted with a number of outside individuals and organizations. Prof. Roth has given invited talks at the IEEE Conference on Plasma Science in St. Louis; at Cornell University, where he also interacted with John Nation and the ion beam plasma group; at the University of Illinois, in October, 1985; and at the University of Texas at Austin, in November, 1985. Professor Roth also attended the International Conference on Plasma Physics in Goteborg, Sweden in June, 1982, and the same conference in Lausanne, Switzerland in late June, 1984. While in Europe, Prof. Roth visited plasma laboratories in Grenoble, France, Garching, West Germany, and Culham, England before or after these conferences.

In the last two years of this contract, the UTK Plasma Science Laboratory was visited by Professor Edward J. Powers of the Electrical Engineering Department of the University of Texas, Austin and Professor George Miley, Chairman of the Nuclear Engineering program at the University of Illinois. Dr. Robert Barker visited on January 20 and 21st, 1985 to give a seminar to faculty and graduate students on his plasma physics work. He also visited on September 18th and 19th, 1985, to give a presentation on Air Force Research programs for our seminar participants, and to evaluate the summer pilot program for undergraduate research assistants. He also visited on March 12 through 14 1986, for the contract signing ceremony and final review of this contract. Finally, Dr. Osmau Ishihara gave a seminar on his work on an MHD-based tokamak current drive

mechanism and discussed possible collaborative research efforts between our laboratory and his own effort in the Electrical Engineering Department of the Texas Tech University in Lubbock, Texas.

In addition to the above interactions, we have been keeping in contact with other Principal Investigators and researchers in the general area of plasma heating and turbulence covered by this contract. At the Annual Meeting of the APS Plasma Physics Division and at the IEEE conference on Plasma Science, we had occasion to interact with individuals doing similar research at the Naval Research Laboratory, at Cornell University, at the Polytechnic University of New York, at the Physics Department at the University Miami at Coral Gables, at the Edwards Air Force Base, at the Kirtland Air Force Base, at the Harry Diamond Laboratories, at the University of Texas at Austin, at Texas Tech University at Lubbock, at the University of Wisconsin, and many other academic laboratories supported by AFOSR, ONR, and the Department of Energy.

STAFFING

Faculty Investigators

This five-year program of research utilized the services of two members of the UTK Electrical Engineering Department faculty, Prof. J. Reece Roth, Principal Investigator, and Prof. David Rosenberg. Their profesional background which is relevant to this contract is described briefly below, and their vitae are included in Appendices A and B.

Professor J. Reece Roth

In the past twenty years, Dr. Roth has authored or co-authored 85 publications, of which 36 were articles in refereed journals, and the remainder of which were internally reviewed NASA reports. Dr. Roth has published in the Physics of Fluids, the Review of Scientific Instruments, the IEEE Transactions on Plasma Science, Physical Review Letters, Plasma Physics, Nuclear Fusion, the Journal of Applied Physics, the Journal of Fusion Energy, the Journal of Nuclear Instruments and Methods, the Journal of Spacecraft and Rockets, Nuclear Technology/Fusion, the Journal of Mathematical Physics, Nature, and elsewhere. In addition to these publications, Dr. Roth has been author or co-author of 89 oral or poster presentations at professional society meetings, nearly all of which report experimental data on his scientific or engineering work. These 89 presentations include 27 full-length papers published in conference proceedings.

While at the NASA Lewis Research Center, Dr. Roth made two pioneering contributions to fusion-related superconducting magnet technology. He was responsible for the basic design and distinctive features of the "Pilot Rig" superconducting magnet facility at NASA Lewis in Cleveland. This facility went into service in December, 1964, and was the first such facility ever to be used for plasma physics or controlled fusion research. Dr. Roth's second contribution in the magnet field was as the engineer responsible for the basic design and distinctive features of the NASA Lewis superconducting bumpy torus magnet facility. This facility was the first anywhere in the world to generate a toroidal magnetic field.

In studying the plasma which these facilities were designed to confine, Dr. Roth discovered two previously unrecognized modes of plasma instability. The first of these is the "continuity-equation oscillation" (the name is Dr. Roth's own) which was observed in the Pilot Rig in 1967. Dr. Roth was the first to investigate this oscillation experimentally, and the first to describe it theoretically. His work on the continuity-equation oscillation has been recognized in standard monographs and compilations such as A. I. Akhiezer et al. Plasma Electrodynamics, and F. Cap's Handbook on Plasma Instabilities, Vol. 1. Dr. Roth was also the first to report the experimental observation of the "Geometric Mean Plasma Emission" (Dr. Roth also named this instability). His data were explained theoretically by Professor Igor Alexeff, and they jointly reported the discovery of this new instability in August, 1979.

Dr. Roth initiated research on the electric field bumpy torus concept, an approach to creating a plasma of fusion interest in which strong radial electric

fields are imposed on a bumpy torus plasma, in such a way that they contribute to the heating, stability, and confinement of the plasma.

Dr. Roth has authoritative knowledge of Penning discharges; the use of superconducting magnet facilities in plasma and fusion applications; the continuity-equation oscillation and moving striations; ion heating and transport in a modified Penning discharge; high temperature plasma physics; fusion energy; and fusion technology. Dr. Roth was the first to identify the physical mechanism responsible for ion heating in a modified Penning discharge, and the first to describe it. Dr. Roth's academic responsiblilities have included teaching a required undergraduate course on plasma engineering from his own notes, a three-quarter graduate sequence on fusion energy, al[illegible] from his own notes, a three-quarter doctoral level course on plasma [illegible] and intensive one-week minicourses on Fusion Diagnostics and Fusio[illegible]nergy, which have attracted students from all over th[illegible]ited States and Canada.

Professor David Rosenberg

Dr. David Rosenberg obtained his Doctor of Science in Engineering from New York University in 1964, and has been an Associate Professor in the UTK Electrical Engineering Department since September 1, 1967. Dr. Rosenberg has introduced and taught a wide variety of undergraduate and graduate courses at UTK in communications, including microwave electronics, electromagnetic wave propagation (at the graduate level), introductory microwave networks, microwave networks, guided waves,

electromagnetic fields at the graduate level, and modern transform methods. Professor Rosenberg has consulted for the Army Research Office in Tullahoma, Tennessee, for the USAF Systems Command in Tullahoma, Tennessee, and for the NASA Marshall Space Flight Center in Huntsville, Ala. Prof. Rosenberg has been affiliated on a part time basis with the UTK Plasma Science Laboratory for the last two years of this contract and has contributed to the development of our broadband, absolutely calibrated antennas, to our microwave scattering diagnostic system, and to all aspects of our work that involve microwave or RF technique.

Staff and Graduate Research Assistants

The five year staffing of this contract is shown on Table 2. The five years are shown in the first column with the contract duration and personnel involved during that year in the second and third columns. The status of the personnel are listed on the fourth column along with the duration of time during the 12 month contract that they were affiliated with it. The fraction of the time which they were paid to devote to the contract while they were employed under it is indicated in the 6th column. The highest degree obtained by the individual at UTK during or after his association with this contract is on the 7th column, and whether or not that individual did his thesis research in the UTK Plasma Lab is indicated in the 8th column. The penultimate column lists the institution at which the individual is now working, or was

last known to be working, and his current status at that institution is indicated in the last column.

Undergraduate Research Assistants

It is proposed to continue in future years the very successful Undergraduate Research Assistant pilot program which was initiated at the UTK Plasma Science Laboratory in the summer of 1985. We have hired 9 undergraduate research assistants at a cost of $2000 each, with no university overhead, for the summer of 1986.

The pilot program in the summer of 1985 ended with a banquet hosted by the Dean of Engineering at UTK, William Snyder, which was attended by Dr. Robert Barker; Tom Collins, UTK Vice Provost for Research; and the students who participated in the summer program. The students were asked to spend most of their time on a single project during the summer, and to write this project up at the end of summer. This documentation of the student projects was forwarded to AFOSR program management, along with a program evaluation form that each of the students was asked to fill out. The students were very enthusiastic about their summer experience, and all claim to have learned a great deal from their experience in the UTK Plasma Science Laboratory. At least five out of the six plan to go on to graduate study in electrical or closely allied areas of engineering.

Student Training and Development

During this five-year contract, travel funds were set aside for our graduate assistants, where this was necessary to their training and development. In the last several years, we have made it a custom to take at least our most senior graduate research assistant with us to the IEEE and APS plasma meetings, and did this even on years when these meetings were west of the Mississippi River.

We intend to continue our weekly plasma seminar, the program of which for the past several academic years is in Appendix H of this report, and we also have broadened the horizons of our graduate research assistants by having them travel to other universities as well as to meetings. Our graduate research assistants have also accompanied Prof. Roth on screening trips for surplus equipment at various DoD installations, which are within a half-day's driving radius of Knoxville.

REFERENCES

1. Roth, J. R.; Alexeff, I.; and Mallavarpu, R.: New Mechanism for Electromagnetic Emission near the Geometric Mean Plasma Frequency Phys. Rev. Lett., Vol. 43, No. 6, 445-449, August 6, 1979.

2. Alexeff, I.; Roth, J. R.; Birdwell, J. D.; and Mallavarpu, R.: Electromagnetic Emission and Anomalous Resistivity from Equal and Oppositely Directed Electron Beams. Physics of Fluids, Vol. 24, No. 7, 1348-1357(1981).

3. Penning, F. M.; and Nienhuis, K.: Construction and Application of a New Design of the Phillips Vacuum Gauge. Philips Technical Review II, No. 4 (1949) pp. 116-122.

4. Roth, J. R.: Modification of Penning Discharge Useful in Plasma Physics Experiments. RSI 37, No. 8, Aug. 1966, pp. 1100-1101.

5. Hayman, P. W.; and Roth, J. R.: RF Emission, Nonlinear Mode Coupling, and Ion Thermalization in a Modified Penning Discharge Plasma. APS Bulletin Vol. 26, p. 1061 (1981).

6. J. M. Berger, W. A. Newcomb, J. M. Dawson, E. A. Frieman, R. M. Kulsrud, and A. Lenard "Heating of a Confined Plasma by Oscillating Electromagnetic Fields", Physics of Fluids, Vol. 1, No. 4, (1858) pp. 301-307.

Appendix A

February, 1986

PROFESSIONAL RESUME

J. Reece Roth
Department of Electrical Engineering
The University of Tennessee
Knoxville, Tennessee 37996-2100
(615) 974-4446
FTS 855-4446

PII Redacted I. [redacted]

II. EDUCATIONAL

College: Massachusetts Institute of Technology, graduated in June 1959 with a S.B. in Physics.

Graduate: Entered Cornell University in September 1959, graduated in June 1963 with the Ph.D. Major: Engineering Physics. Minor subjects: Magnetohydrodynamics and Astrophysics.

III. PROFESSIONAL EXPERIENCE

1. Summer 1957, Engineering Aide at Aerojet-General Corporation, Azusa, California. Carried through a study of the electromagnetic flowmeter as a means of measuring the exhaust velocity of rocket engines.

2. Summer 1958, worked as an Engineering Aide at Aerojet-General with the Rover Project (the nuclear rocket propulsion program).

3. Summer 1959, worked as an Aerospace Engineer with the electrical propulsion group at Rocketdyne, a division of North American Aviation.

4. 1963 to 1978, Member of the Plasma Physics Branch of the Physical Science Division at the NASA Lewis Research Center in Cleveland, Ohio. Was Principal Investigator of the NASA Lewis Bumpy Torus Project.

5. September 1978 to June, 1982. Visiting Professor of Electrical Engineering, University of Tennessee, Knoxville. Principal Investigator of two research contracts in the field of electric field dominated plasma, one with the ONR, the other with AFOSR. These contracts provided half-time support for the Principal Investigator and 4 Research Assistants. A third contract with TVA provided support for one graduate student for studies in the field of fusion energy, and retainer-type consulting for the Principal Investigator. In addition to research, taught a junior level course on plasma engineering, a graduate

sequence on fusion technology, plasma diagnostics, and physics of fusion, also taught one-week minicourses on fusion energy and fusion diagnostics.

6. June 1982 to August, 1983. Research Professor, Department of Physics. Continuation of contract research, and teaching of graduate sequences in fusion energy and plasma physics.

7. September 1983 to present. Professor of Electrical Engineering and Chairman of the departmental Plasma Engineering Curriculum Committee. Continuation of contract research, and teaching of a graduate course sequence in Plasma Diagnostics, a senior-level course "Introduction to Fusion Energy," and a junior-level course in Plasma Engineering. Presently in the final stages of preparing a textbook, "Introduction to Fusion Energy".

IV. CONTRACTS AND EXTERNAL SUPPORT

Principal Investigator of contracts with ONR, AFOSR, and TVA which, since 1980, have totaled $927,225 as of December 31, 1985, and will bring in $1,417,870 by the time present contracts run out in early 1989. These contracts have yielded overhead of 189,906 as of Dec. 31, 1985, and will bring in a total overhead of $368,385 to the University when present contracts run out. They also have provided $278,464 in special equipment grants which have been used to purchase new, state-of-the art diagnostic equipment for the UTK Plasma Science Laboratory. These contracts also made it possible to acquire surplus instruments and equipment from the Department of Defense with a replacment value of exceeding one million dollars. These contracts will provide 4.50 man-years of faculty support and 34.7 student-years of support when the last signed contract runs out.

V. HONORS, AWARDS, AND LISTINGS

Relevant student honors include a four-year Alfred P. Sloan Scholarship at M.I.T., Presidency of the M.I.T. Rocket Research Society, the 1957 American Rocket Society-Chrysler Corporation's Student Award, and a Ford Fellowship at Cornell. Life Member of Sigma Xi, Fellow of IEEE, and co-recipient of one of NASA's "Awareness" awards to the Bumpy Torus Project. Listed in "Who's Who in the Midwest," 1970 to 1978 Editions; "Who's Who in the South and Southwest, "17th Edition, Who's Who in America, 43rd and 44th Editions, American Men & Women of Science, 15th Edition; Who's Who in Engineering, Fourth Edition; Who's Who in Technology Today, 4th Edition, and Who's Who in Frontier Science and Technology, 1st and 2nd Editions.

VI. PROFESSIONAL SOCIETY MEMBERSHIPS

1. Fellow of the IEEE
2. Life member of Sigma Xi
3. Life member of the AAAS
4. Member of the American Physical Society
5. Member of the AIAA
6. Member of the American Nuclear Society
7. Member of American Society for Engineering Education
8. Member of the IEEE Nuclear and Plasma Sciences Society
9. Member of the Archaeological Institute of America

VII. PROFESSIONAL SOCIETY ACTIVITIES

1. Associate Editor, IEEE Transactions on Plasma Science, 1973-Present.
2. Elected Member-at-Large of Administrative Committee, IEEE Nuclear and Plasma Sciences Society, 1974-77.
3. Secretary, NPSS Administrative Committee, 1975.
4. Organizing Committee, IEEE Plasma Science and Applications Committee, 1971-73.
5. Elected Member, Executive Committee of IEEE Plasma Science and Applications Committee, 1974-77, 1980-82, 1985-87.
6. Member of the Program Committee, IEEE International Conferences on Plasma Science, 1974, 1975.
7. Member, Executive Committee, Northern Ohio Section of the American Nuclear Society, 1975-1978.
8. Member, AIAA Plasmadynamics Technical Committee, 1979 to 1981.
9. Director, and Member of Executive Committee, East Tennessee Section of the IEEE, 1982-83.
10. Vice Chairman, East Tennessee Section of the IEEE, 1983-84.
11. Chairman, East Tennessee Section of the IEEE, 1984-85.
12. Vice President, UTK Chapter of Sigma Xi, 1984-85.
13. President, UTK Chapter of Sigma Xi, 1985-86.

VIII. PROFESSIONAL ACCOMPLISHMENTS

In the past twenty years, Dr. Roth has authored or co-authored 102 archival publications, of which 37 were articles in refereed journals, 28 were full-length papers in reviewed conference proceedings, and the remainder of which were internally reviewed NASA reports. Dr. Roth has published in the Physics of Fluids, the Review of Scientific Instruments, the IEEE Transactions on Plasma Science, Physical Review Letters, Plasma Physics, Nuclear Fusion, the Journal of Applied Physics, the Journal of Fusion Energy, the Journal of Nuclear Instruments and Methods, the Journal of Spacecraft and Rockets, Nuclear Technology/Fusion, the Journal of Mathematical Physics, Nature, and elsewhere. In addition to these publications, Dr. Roth has been author or co-author of 78 oral or poster presentations at professional society meetings, nearly all of which report experimental data on his scientific or engineering work.

While at the NASA Lewis Research Center, Dr. Roth made two pioneering contributions to fusion-related superconducting magnet technology. He was responsible for the basic design and distinctive features of the "Pilot Rig" superconducting magnet facility at NASA Lewis in Cleveland. This facility went into service in December, 1964, and was the first such facility ever to be used for plasma physics or controlled fusion research. Dr. Roth's second contribution in the magnet area was as the engineer responsible for the basic design and distinctive features of the NASA Lewis superconducting bumpy torus magnet facility. This facility went into service in 1972, and was the first superconducting magnet facility anywhere in the world to generate a toroidal magnetic field.

In studying the plasma which these facilities were designed to confine, Dr. Roth discovered two previously unrecognized modes of plasma instability. The first of these is the "continuity-equation oscillation" (the name is Dr. Roth's own) which was observed in the Pilot Rig in 1967. Dr. Roth was the first to investigate this oscillation experimentally, and the first to describe it theoretically. His work on the continuity-equation oscillation has been recognized in standard monographs and compilations such as A. I. Akhiezer et al. Plasma Electrodynamics, and F. Cap's Handbook on Plasma Instabilities, Vol. 1. Dr. Roth was also the first to report the experimental observation of the "Geometric Mean Plasma Emission" (Dr. Roth also named this instability). His data were explained theoretically by Professor Igor Alexeff, and they jointly reported the discovery of this new instability in August, 1979.

Dr. Roth initiated research on the electric field bumpy torus concept, an approach to creating a plasma of fusion interest in which strong radial electric fields are imposed on a bumpy torus plasma, in such a way that they contribute to the heating, stability, and confinement of the plasma.

Dr. Roth has authoritative knowledge of Penning discharges; the use of superconducting magnet facilities in plasma and fusion applications; the continuity-equation oscillation and moving striations; ion heating and transport in a modified Penning discharge; high temperature plasma physics; fusion energy; and fusion technology. Dr. Roth was the first to identify the physical mechanism responsible for ion heating in a modified Penning discharge, and the first to describe it. Dr. Roth's academic responsibilities have included teaching a required undergraduate course on plasma engineering from his own notes, a three-quarter senior and graduate level sequence on fusion energy, also from his own notes, a three-quarter graduate course in Plasma Diagnostics which includes one quarter of laboratory, a three-quarter doctoral level course on plasma physics, and intensive one-week minicourses on Fusion Diagnostics and Fusion Energy, which have attracted students from all over the United States and Canada. He is now in the final stages of publishing a senior and first year graduate level textbook, "Introduction to Fusion Energy."

BIOGRAPHICAL SKETCH: DAVID ROSENBERG

PII Redacted 1. [redacted]

2. Academic Rank:

   Associate Professor of Electrical Engineering (Full-Time)

3. Degree, with Field, Institution and Date:

   B.S.E.E., CUM LAUDE, New York University, 1953
   M.S.E.E., New York University, 1954
   D. Eng. Sc., New York University, 1964

4. Number of years service on this Faculty: 19

   Original appointment - September 1, 1965 - Assistant Professor of Electrical Engineering
   Promotion to Associate Professor of E.E. in Sept. 1, 1967

5. Other Related Experience - Teaching and Industrial:

   Employer - U.S. Coast Guard
   Period - 1946-1949
   Position - Loran-A Electronics Technician

   Employer - New York University, School of Engineering and Science
   Period - 1954-1962
   Position - Instructor of Electrical Engineering, Summer Research on U.S. Air Force and NASA Contracts

   Employer - New York University, School of Engineering and Science
   Period - 1962-1964
   Position - Research for Doctorate, U.S. Army Grant for Research

   Employer - The University of Tennessee
   Period - 1965 - Present
   Position - Assistant Professor of EE (1965-1967)
   Associate Professor of EE (since 1967)
   U.S. Air Force Research Contract (1967-1968)(1983-1984)
   NASA Research (1970)

6. Consulting:

   ARO, Tullahoma, Tennessee

   USAF Systems Command, Tullahoma, Tennessee

   NASA, Huntsville, Alabama

7. States in which registered: None

8. Publications

Masters Thesis, "Voltage Regulation of a Transmission Line as a Function of Terminating Admittance," New York University May 1954.

Doctoral Thesis, "Fields in A Closed, Periodically Thin-Iris Loaded, Uniform Waveguide, New York University, June 1964.

"On Planar Obstacles for Periodically and Interdigitally Loaded Waveguides," URSI Meeting, Dartmouth, N.H., (with D.J.R. Stock), October 1965.

"Some Results for Thin-Iris Loaded Periodic Waveguides," MIT Transactions of IEEE (with D.J.R. Stock), MIT-14, No. 3, March 1966, pp. 145-153.

"A Graphical Method for Determining the Q of a Resonant R-F Cavity," ARO, VKF/LR-AP-61 (with C.P. Enis), October 1966.

"Complex Propogation Constants for Closed, Lossless, Periodic Waveguides," URSI Meeting, Washington, D.C. (with D.J.R. Stock), April 1967.

"Evaluation of the Use of a Multiplexing Monitor to Troubleshoot Electronic Systems," NASA, R-ASTR-G-WP-4-68 (with P.R. White), February 1968.

"A Multimoded Cavity Probe to Provide High Spatial Resolution of Wake Trial Ionization Measurement," AEDC-TR-69-32, February 1969.

"Coupled Striplines of Asymmetric Crossection," Proceedings of the 8th Annual IEEE Region III Convention, Huntsville, Alabama (with V.W. Ramsey), No. 69-C-46, November 1969, pp. 341-346.

"Data Smoothing Operations with Associated Physical Significance," USNC/URSI Meeting, Los Angeles, California (with C.S. Hsieh), October 1971.

"An Analytical Model for Optical Determination of Respirable Coal Dust Particle Size," Proceedings of the 10th Annual IEEE Region III Convention, Knoxville, Tennessee (with T.F. King, G.W. Hoffman, and J.C. Hung), Pub. No. 72-C-HO-591-8 REG III, April 1972, pp V3-1 to V3-3.

"Design Criteria of a Universal Compandor for the Elimination of Audible Noise in Tape, Disc, and Broadcast Systems," Journal of AES (with M.G. Duncan and G.W. Hoffman), Vol. 23, No. 8, October 1975, pp. 610-622. Also Presented at AES 49th Convention, New York, N.Y. August 1974. Also Presented at 12th Annual IEEE Region III Convention, Clemson S.C., April 1976.

"A Calibrated, Broadband Antenna for Plasma RF Emission Measurements Below 1 GHz." 1984 IEEE International Conference on Plasma Sciene (with Paul D. Spence, J. Reece Roth), St. Louis, MO., May 14-16, 1984.

"Broadband RF Emission and Electron Number Density Measurements of an Electric Field Dominated Plasma." 1984 IEEE International Conference on Plasma Science (with J. Reece Roth, Paul D. Spence), St. Louis, MO., May 14-16, 1984.

"Correlation of RF Emission, Plasma Wave Propagation, and Plasma Turbulence in Classical and Modified Penning Discharges." 1984 International Conference on Plasma Physics (with J. Reece Roth, Paul D. Spence, Larry R. Baylor, Peyman Denkordi), Lausanne, Switzerland, June 27-July 3, 1984.

9. Scientific and Professional Societies of which a member:

IEEE (MTT-S, AP-S), Reviewer Trans. MTT-S (1972)

ASEE, UT Executive Committee (1966-9, 77-8)

AMS

AAUP

10. Honors and Awards:

U.S. Coast Guard Loran Station Operation Award

B.S.E.E. Awarded CUM LAUDE (1953)

S.B. Duryea Graduate Fellowship (1953-54)

ARO, August, 1967 Monthly Best Work Award

NASA Apollo 10 Flight Contribution Award

Tau Beta Pi Member

Eta Kappa Nu Member

Sigma Xi Member

11. Subjects or courses taught this year by term:

Fall 1983	Hours	Lecture	Lab	Day	Eve	Ext.	Grad.
EE 3060	3	X	X	X			
EE 4080	3	X		X			
EE 4089	0		X				
EE 5870	3	X			X		X

	Hours	Lecture	Lab	Day	Eve	Ext.	Grad.
Winter 1984							
EE 3060	3	X	X	X			
EE 5360	3	X			X		X
EE 3110							
Spring 1984							
EE 3060	6	X	X	X			
EE 3069							
EE 6610	3	X			X		X

12. Other Assigned Duties Performed During the Academic Year:

Electrical Engineering Department Representative to U.T. Library Committee

Field and Communications Curriculum Committee

Ph.D. Prelim Exam Committees

Master's Thesis Examination Committee (for E.J. Kent)

Graduate and Undergraduate Advising

College and Department Faculty Meetings

13. List Specific Programs in Which Faculty Member has Participated to Improve Teaching and Professional Competence.

Appalachian Science Fair Judging Committee, Knoxville

U.T. Graduate School Professional Development Award for Undergraduate Curricular Update.

Graduate Courses Introduced and Taught at U.T.:

Microwave Electronics (EE 5850)

Electromagnetic Wave Propagation (EE 5860)

Introductory Microwave Networks (EE 5870)

Microwave Networks (EE 6610-20-30)

Guided Waves (EE 6670-80-90)

Publications and Presentations
Supported by AFOSR 81-0093

1. Roth, J. R.; Hayman, P. W.; and Pastel, R. L.: "A Paired Comparison of High Frequency RF Emission from Two Configurations of Electric Field Dominated Plasma," Proceedings of the International Conference on Plasma Physics, Goteborg, Sweden, June 9-15, 1982, p. 250.

2. Roth, J. R.; Hayman, P. W.; and Pastel, R. L.; "A Paired Comparison of High Frequency RF Emission from Two Configurations of Electric Field Dominated Plasma," Conference Record, 1982 IEEE International Conference on Plasma Science, May 17-19, 1982, Ottawa, Ontario, p. 65 IEEE 82CH1770-7 NPS, (1982).

3. Pastel, R. L.; Roth, J. R.; and Spence, P. D.; "Parallel Electric Fields and Anomalous Resistivity in a Classical Penning Discharge", APS Bulletin 27, No. 8, Pt. II, p. 1106, (1982).

4. Pastel, R. L.; and Roth, J. R.: "Axial Electric Fields and Electron Number Density Profiles in a Classical Penning Discharge", APS Bulletin, Vol. 28, No. 8, pp. 1256-1257, (1983).

5. Spence, P.D.; Rosenberg, D.; and Roth, J. R.: "A Calibrated, Broadband Antenna for Plasma RF Emission Measurements Below 1 GHz". Paper 3R4, Conference Record, IEEE 84CH1958-8, 1984 IEEE International Conference on Plasma Science, May 14-16, St. Louis, Missouri, p. 73 (1984).

6. Baylor, L. R.; Dehkordi, P.; and Roth, J. R.: "Microwave Scattering and Electrostatic Turbulence Experiments on a Classical Penning Discharge", Paper 3R5, Conference Record, IEEE 84CH1958-8, 1984 IEEE International Conference on Plasma Science, May 14-16, St. Louis, Missouri, p. 73, (1984).

7. Roth, J. R.; Spence, P. D.; Baylor, L. R.; Rosenberg, D.; and Dehkordi, P.: "Correlation of RF Emission, Plasma Wave Propagation, and Plasma Turbulence in Classical and Modified Penning Discharges", Paper P1-12, Proceedings of the International Conference on Plasma Physics, Lausanne, Switzerland, June 270July 3, 1984, p. 13.

8. Laroussi, M.; Baylor, L. R.; Dehkordi, P.; and Roth, J. R.: "Anomalous Drift Waves Detected with Microwave Scattering in an Electric Field Dominated Plasma", Paper 1W-4, APS Bulletin, 29, No. 8, p. 1197, (1984).

9. Roth, J. R.; and Alexeff, I.: "Growing Waves and Electromagnetic Emission from Two Oppositely Directed Electron Beams in a Cold Background Plasma", Paper 1W-10, APS Bulletin 29, No. 8, p. 1198, (1984).

10. Roth, J. R.; and Laroussi, M.: "Collisional Magnetic Pumping Revisited", Paper 4R-7, Conference Record, IEEE 85 CH 2199, 1985 IEEE International Conference on Plasma Science, June 3-5, 1985, Pittsburgh, PA, p. 72 (1985).

11. Laroussi, M.; Spence, P.D.; Rosenberg, D.; Mannone, J. C.; and Roth, J. R.: "RF Emission Power and Its Dependence on Plasma Parameters and Turbulence in a Classical Penning Discharge", Paper 51 Conference Record, IEEE 85 CH 2199, IEEE International Conference on Plasma Science, June 3-5, 1985, Pittsburgh, PA, p. 84 (1985).

12. Roth, J. R.; and Laroussi, M.; Enhanced Plasma Heating by Collisional Magnetic Pumping", APS Bulletin, Vol. 30, No. 9 (1985) p. 1390.

13. Laroussi, M.; Spence, P.D.; Rosenberg, D.; Ghayspoor, R.; and Roth, J. R.: RF Emission Power Measurement and Anomalous Drift Wave Study in a Classical Penning Discharge", APS Bulletin, Vol. 30, No. 9 (1985) p. 1397.

14. Rosenberg, D.; Spence, P. D.; Laroussi, M., and Roth, J. R.: "Scaling of Radiated RF Power for Classical and Modified Penning Discharges", APS Bulletin, Vol. 30, No. 9, (1985) p. 1551.

15. Laroussi, M.: "Plasma Heating by Collisional Magnetic Pumping", Proc. 18th Southeastern Symposium on Systems Theory, April 7-8, 1986 ISSN 0094-2898, pp. 475-479.

16. Laroussi, M.; and Roth, J. R.: "Plasma Heating by Collisional Magnetic Pumping", Paper 5D6, Proc. 13th IEEE International Conf. on Plasma Science, Saskatoon, Canada, May 19-21, 1986.

Appendix D

ABSTRACTS OF CONFERENCE PRESENTATIONS

Oral Session 3E
PLASMA WAVES, INSTABILITIES AND ANTENNAS
Tuesday, May 18, 1982
9:00 A.M., Room 253, Mackenzie Building
Session Chairman - I.P. Shkarofsky

3E1 A PAIRED COMPARISON OF HIGH FREQUENCY RF EMISSION FROM TWO CONFIGURATIONS OF ELECTRIC FIELD DOMINATED PLASMA*

J. Reece Roth, P. W. Hayman, and R. L. Pastel
Department of Electrical Engineering
University of Tennessee
Knoxville, TN 37996-2100

We report paired comparison observations of RF emission from two electric field dominated plasmas over the range from 1.0 MHz to 70 GHz. One of these plasmas is a classical Penning discharge configuration with a plasma length of about 80 centimeters, a diameter of about 10 centimeters, and an approximately flat axial magnetic field of up to 0.4 Tesla. The second plasma (generated in a separate apparatus) is a modified Penning discharge operated in a magnetic mirror configuration with an axial mirror ratio of 5:1, intended to simulate magnetospheric plasmas. This plasma has approximately the same dimensions as the first, and maximum magnetic fields at the mirror throats of up to 0.4 Tesla. Both plasmas are electric field dominated in the sense of having strong radial and/or axial electric fields penetrating the plasma. Both are operated steady-state in helium and argon gas, and both are enclosed in glass vacuum systems which allow RF radiation to escape the plasma without forming a resonant cavity. The instrumentation available allows a continuous spectrum of RF emission up to 1 GHz to be displayed, and measurements to be made at isolated microwave frequency bands up to 70 GHz.

At the time of writing, no information is available on the RF emission characteristics of the classical Penning discharge. The RF emissions from the modified Penning discharge have recently been found to have several interesting characteristics. In addition to the previously reported[1,2] geometric mean emission frequency, in the range from 10 to 40 MHz at background pressures below 2.4×10^{-4} Torr of Helium, we recently observed a low frequency peak, the fundamental of which is about 5 MHz, and which exhibits up to 30 or 50 harmonics before fading into the turbulent background. This peak occurs above 2.4×10^{-4} Torr, and the nonlinear mode coupling exhibited by its harmonic generation is sometimes visible up to 1 GHz. This "type II" emission appears to be related to rotating spokes driven by $E\times B/B^2$ drift, which are a consequence of the diocotron instability.

The modified Penning discharge also exhibits RF emission at frequencies above 1 GHz, including the 1 cm band at 26 GHz at which the microwave interferometer operates. The origin and nature of these high frequency emissions are a matter for continuing study.

1.) I. Alexeff, J. R. Roth, J. D. Birdwell, and R. Mallavarpu: Electromagnetic Emission and Anomalous Resistivity from Equal and Oppositely Directed Electron Beams, Phys. Fluids Vol. 24, No. 7 (1981) pp. 1348-57.
2.) P. W. Hayman and J. R. Roth: RF Emission, Nonlinear Mode Coupling, and Ion Thermalization in a Modified Penning Discharge Plasma, APS Bulletin Vol. 26, No. 7 (1981) p. 1061.

*The work on the classical Penning discharge was supported by AFOSR contract #81-0093, and the work on the modified Penning discharge by ONR contract #N0014-80-C-0063.

8R 16 Parallel Electric Fields and Anomalous Resistivity in a Classical Penning Discharge. ROBERT L. PASTEL, J. REECE ROTH, AND PAUL D. SPENCE, Univ. of Tennessee, Knoxville, TN 37996-2100.*

We have operated a steady-state plasma in a classical Penning discharge configuration[1] with a uniform axial magnetic field and measured the floating potential profile along the axis of symmetry. The total potential drop is on the order of kilovolts, implying an extreme degree of anomalous resistivity. A special high-voltage floating Langmuir probe was developed for these measurements, capable of at least 5 kilovolts without breakdown. Previous exploratory measurements[2] of RF emissions over the range from 0.5 to 1000 MHz were extended and correlated with the electric field profile measurements. The axial potential profile was also observed in conjunction with ion energy measurements made with a retarding potential analyzer.

*Supported by Contract AFOSR-81-0093 (Roth).

1. F. M. Penning and K. Nienhuis, Philips Tech. Rev. Vol. 11, 116 (1949).
2. J. R. Roth, P. W. Hayman, and R. L. Pastel, Paper 11P-II-02, Proc. 1982 Int. Conf. on Plasma Physics, Goteborg, Sweden, p. 250.

9U 5 Axial Electric Fields and Electron Density Profiles in a Classical Penning Discharge.* ROBERT L. PASTEL and J. REECE ROTH, University of Tennessee, Knoxville, TN 37996-2100.

We have operated a steady-state classical Penning discharge in a uniform magnetic field up to 0.4 Tesla. The electrons are trapped in an axial electrostatic potential well, and form two interpenetrating beams. The cylindrical discharge is about 10 cm in diameter and about 60 cm long. Recent modifications to the water-cooled cathodes have made it possible to draw currents above 0.5 amperes at anode potentials of several kilovolts. The electron number density for these conditions is above $10^{10}/cm^3$. These conditions have made possible RF emission amplitudes more than 20 dB higher than those previously observed, and also the observation of significant RF emission up to 2 GHz. The principal emission mechanisms appear to be at the geometric mean frequency and at the electron plasma frequency. The frequency spectrum is white noise-like from below 0.6 MHz to above 1.0 GHz. Data taken with a retarding potential energy analyzer show axial ion energy distribution functions which range from Monoenergetic to Maxwellian.

*Supported by contract AFOSR-81-0093.

3R4

A CALIBRATED, BROADBAND ANTENNA FOR PLASMA RF EMISSION MEASUREMENTS BELOW 1 GHz*

Paul D. Spence
Department of Engineering Science and Mechanics
and
David Rosenberg
J. Reece Roth
Department of Electrical Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

A constant impedance, constant aperture antenna can make possible broadband plasma RF emission measurements which yield relative and absolute power levels. However, good technique, such as that described by Heald and Wharton [1], must be followed for the immersion of such an RF probe into plasma radiation.

We have used a complementary conical spiral antenna, similar to that described by Rumsey [2], to observe plasma RF emission over the frequency range $100 \leq \nu \leq 1200$ MHz. The RF emission was emitted by a modified Penning discharge as described by Roth [3] and Roth, Hayman, and Pastel [4]. The RF emission from the discharge typically exhibits harmonic structure over a broad frequency range, necessitating a broadband antenna with a flat frequency response curve to allow detailed spectral analysis.

The antenna consists of two metal strips of approximately uniform width wound helically on a cone made of Lexan plastic. Since the antenna is a balanced network, a balun is employed to make the transition to a 50-ohm coaxial line. The antenna feed method is critical in maintaining a uniform impedance network. Neglecting stray transmission line effects, the probe circuit for the frequency range $100 \leq \nu \leq 500$ MHz is 50 ohms due to the spectrum analyzer, paralleled by 291 ohms due to balun magnetization; the combination is fed by a 144 ohm probe aperture (see Fig. 1). Above 500 MHz, the balun seems to behave nonuniformly and requires further fine tuning to achieve a satisfactory frequency response and an accurate calibration over the frequency range from 500 MHz to 1.0 GHz. Below 100 MHz, it is not clear that the antenna remains properly immersed in the plasma radiation under present laboratory conditions.

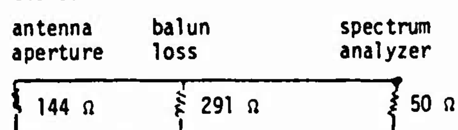


Figure 1

1. M. A. Heald and C. B. Wharton, Plasma Diagnostics With Microwaves, Krieger Publishing, New York, 1978.
2. V. Rumsey, Frequency Independent Antennas, Academic Press, New York, 1966.
3. J. R. Roth, Modification of Penning Discharge Useful in Plasma Physics Experiments, RSI, 37 (1966), 1100-1101.
4. J. R. Roth, P. W. Hayman, and R. L. Pastel, A Paired Comparison of High Frequency RF Emission from Two Configurations of Electric Field Dominated Plasma, Proc. 1982 Int. Conf. on Plasma Physics, Goteborg, Sweden.

*Supported in part by ONR Contract #N00014-80-C-0063 and in part by AFOSR contract #81-0093.

3R5

MICROWAVE SCATTERING AND ELECTROSTATIC TURBULENCE EXPERIMENTS ON A CLASSICAL PENNING DISCHARGE

Larry R. Baylor
Peyman Dehkordi
J. Reece Roth

Department of Electrical Engineering
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Knoxville, Tennessee 37996-2100

We have operated a steady-state classical Penning discharge in a uniform magnetic field up to 0.4 Tesla. The electrons are trapped in an electrostatic potential well, and form two interpenetrating beams in the plasma, the midplane diameter of which is about 10 cm, and the length of which is about 60 cm along the axis. This plasma supports high levels of plasma turbulence, axial electric fields of several tens of volts per centimeter, and emits broadband electromagnetic radiation over the frequency range from below 1 MHz to more than 2 GHz [1,2].

Measurements from a microwave scattering apparatus consisting of a 27 GHz Gunn diode in a homodyne mixer configuration are presented. The microwaves are incident on the plasma in the ordinary mode at a power level of approximately 100 milliwatts. The scattered microwave power is observed in a plane normal to the magnetic field, for scattering angles from 20° to 160°. The scattered signal is fed to a crystal detector and is then displayed on a spectrum analyzer. Electron number density fluctuations are observed in the frequency range from 10 to 40 kHz. Preliminary data suggest that the density fluctuations obey a linear dispersion relation.

Data have been taken for various plasma conditions in conjunction with an analog-to-digital data handling system which analyzes a digital time series of electrostatic potential fluctuations taken from azimuthally placed capacitive probes. This system obtains auto- and cross-power spectra, coherence, dispersion relations, and the phase angle as a function of frequency. In these experiments the electron number densities range from 10^9 to 10^{10}/cubic centimeter, the magnetic field ranges from 0.2 to 0.4 Tesla, and the discharge current ranged up to 0.5 amperes.

The data fromthe microwave scattering diagnostic is correlated with data from the electrostatic turbulence diagnostic and with the plasma operating conditions. If progress on the research program allows, data will be reported on the absolute value and frequency dependence of RF emissions at frequencies up to 1.0 GHz.

[1] J. R. Roth, Paul P. W. Hayman, and R. L. Pastel, A Paired Comparison of High Frequency RF Emission from Two Configurations of Electric Field Dominated Plasma, Proceedings of the 1982 International Conference on Plasma Physics, Goteborg, Sweden.
[2] R. L. Pastel and J. R. Roth, Axial Electric Fields and Electron Density Profiles in a Classical Penning Discharge, APS Bulletin, Vol. 28, No. 8 (1983) 1256-57.

*Supported by AFOSR contract #81-0093.

1W4 Anomalous Drift Waves Detected with Microwave Scattering in an Electric Field Dominated Plasma.* LARRY R. BAYLOR, J. REECE ROTH, PEYMAN DEHKORDI AND MOUNIR LAROUSSI, Department of Electrical Engineering, University of Tennessee, Knoxville, TN 37996-2100.-We have operated a steady-state classical Penning discharge in a uniform axial magnetic field of 0.4 Tesla. The electron number density is typically $2 \times 10^9/cm^3$ in helium gas, with T_e = 5-10 eV. We have applied 32 GHz microwave scattering and capacitive probes in conjunction with a two-channel analog-to-digital data handling system which is capable of producing auto and cross power, phase, and coherence spectra. A strong background of electrostatic turbulence was observed, the RMS values of density of which were as high as several percent of the average electron density. The fluctuation spectrum exhibited several peaks between 10 and 50 kHz, which appeared to be the fundamental and sub-multiples of E/B drift waves, characteristic of Penning discharges (1). The frequency of this disturbance was proportional to B, implying a radial electric field, the magnitude of which is proportional to B^2.

1. J. R. Roth, P. D. Spence, L. R. Baylor, D. Rosenberg, and P. Dehkordi, Paper P1-12, 1984 Int. Conf. on Plasma Physics, Lausanne, Switzerland, June 1984.

*Supported by contract AFOSR 81-0093.

1W10 Growing Waves and Electromagnetic Emission from Two Oppositely Directed Electron Beams in a Cold Background Plasma.* --J. REECE ROTH AND IGOR ALEXEFF, University of Tennesee, Knoxville, TN 37996-2100.--We present a generalization of previous theoretical work (1) to the case of two non-relativistic, oppositely directed interpenetrating electron beams of unequal density interacting with a cold background plasma. These conditions can be reduced to a sixth-order cold plasma dispersion relation, which has growing and damped solutions. In the case of two beams, each 1/2 of the total electron density, interacting with cold ions, we recover our previous result (1); growing waves near the geometric mean of the electron and ion plasma frequency. When the beams are much less dense than the cold electron background density, the growing waves are near the electron plasma frequency of the cold electron population. The maximum growth rates are not at the beam electron plasma frequency or at the upper or lower hybrid frequency. The frequency of an oscillator based on this instability can be tuned by adjusting the relative intensity of the two beams as well as the beam density relative to the background plasma.

1.) I. Alexeff, J. R. Roth, J. D. Birdwell, and R. Mallavarpu, Physics of Fluids, 24 (1981) pp1348-57.

*Supported in part by AFOSR contracts 81-0093 and 82-0045, and by ONR contract N00014-80-C-0063.

Collisional Magnetic Pumping Revisited*

J. Reece Roth and Mounir Laroussi

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Department of Electrical Engineering
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Knoxville, TN 37996-2100

Collisional magnetic pumping is achieved by wrapping an exciter coil around a cylindrical plasma, and driving it with relatively low RF frequencies which ultimately transfer energy to the parallel component of the ion velocity. For this form of heating to take place, the period of the driving RF and the collision time should be comparable, and both of these should be much less than the transit time of an ion through the heating region. Berger, et al.[1] have shown that if a sinusoidal perturbation of the confining magnetic field of the form $B = B_0(1 + \delta \cos \omega t)$ is applied, the heating rate is given by

$$\frac{dE}{dt} = \frac{\delta^2 \omega^2 \nu_c}{6(9\nu_c^2/4 + \omega^2)} E \qquad (1)$$

where ω is the driving frequency, ν_c is the collision frequency, $\delta << 1$ is the field modulation[2], and E is the total ion energy. Transfer of energy to the parallel component of the ion velocity occurs because the magnetic moment $v_\perp^2/B$ is approximately constant. There is a small net collisional energy transfer to this parallel component as the magnetic field varies sinusoidally, and the perpendicular components of velocity follow suit. In this original form of collisional magnetic pumping[1,2,3], the sinusoidal variation of $v_\perp^2$ about the mean established outside the heating region left only a very small net energy transfer, which is proportional to the square of the small parameter δ.

In this paper, we explore the consequences of applying to the exciter coil a RF current which is either full wave rectified, $B = B_0 (1 + \delta |\cos \omega t|)$, or which is a sinusoidal excitation with a DC bias magnetic field applied only in the axial region subtended by the exciter coil, $B = B_0 (1 + \delta (1 + \cos\omega t))$. In both these cases, the conservation of the magnetic moment will lead to an increase in the perpendicular components of velocity above the equipartition values outside the exciter coil, but not to a decrease. Thus any stochastic process, including collisions in the heating region, is much more likely to achieve a net energy transfer to the parallel velocity component. This should lead to a heating rate linearly proportional to the modulation δ, rather than to its square, as in Equation 1. If ions are scattered by fluctuating electric fields originating from strong plasma turbulence, this can lead to an effective collision frequency higher than the binary collisional value, and to greatly enhanced ion heating rates.

1. J. M. Berger, W. A. Newcomb, J. M. Dawson, E. A. Frieman, R. M. Kulsrud, and A. Lenard, Physics of Fluids, Vol. 1, No. 4 (1958) pp. 301-307.
2. K. Miyamoto, Plasma Physics for Nuclear Fusion, MIT Press, Cambridge, MA (1980) pp. 440-441.
3. T. Kammash, Fusion Reactor Physics, Ann Arbor Science Publishers, Ann Arbor, MI (1975) 161-182.

*Supported by the Air Force Office of Scientific Research, contract AFOSR 81-0093 (Roth).

5P-3

RF Emission Power and Its Dependence on Plasma Parameters and Turbulence in A Classical Penning Discharge*

Mounir Laroussi, Paul D. Spence, David Rosenberg, John C. Mannone and J. Reece Roth

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We have operated a steady-state classical Penning discharge in a uniform axial magnetic field, the value of which can be varied up to 0.4 Tesla. The electron number density is typically 2 $10^9/cm^3$ in helium gas with Te = 5 - 10 eV. RF emission has been detected with specially developed broad-band planar-spiral and conical-spiral antennas[1], and its absolute integral power has been measured and plotted against electron number density and electron kinetic temperature, with the magnetic field as a parameter. The electron number density and kinetic temperature have been measured with a Langmuir probe inserted into the plasma.

The RF emission spectrum covers a broad-band frequency range between 100 MHz and 1000 MHz. This spectrum is formed by numerous harmonics of fundamental frequencies. The correlation between the RF emission spectra and the results already obtained on the electrostatic turbulence[2,3] due to strong axial and radial electric fields[4] and on wave propagation in the plasma is also investigated.

1. P. Spence, and J. R. Roth, paper 3R3, IEEE International Conference on Plasma Science, St Louis, Missouri, May 1984.

2. M. Laroussi, L. R. Baylor, P. Dehkordi, and J. R. Roth.: "Anomalous Drift Waves Detected with Microwave Scattering in an Electrical Field Dominated Plasma", Paper 1 N-4, APS Bulletin, Vol. 29, No. 8 p. 1197, (1984).

3. J. R. Roth, P. D. Spence, L. R. Baylor, D. Rosenberg, and P. Dehkordi.: "Correlation of RF Emission, Plasma Wave Propagation, and Plasma Turbulence in Classical and Modified Penning Discharges", Paper P 1-12, Proceedings of the International Conference on Plasma Physics, Lausanne, Switzerland, June, 1984.

4. R. L. Pastel, and J. R. Roth.: "Axial Electric Fields and Electron Number density Profiles in a Classical Penning Discharge", APS Bulletin, Vol. 28 No. 8, pp. 1256-1257, (1983).

*Supported by AFOSR contract 81-0093

2Q 2 Enhanced Plasma Heating by Collisional Magnetic Pumping:* J. REECE ROTH and MOUNIR LAROUSSI, Plasma Science Laboratory, University of Tennessee, Knoxville, TN 37996-2100.--In the proper regime, collisional magnetic pumping is achieved by wrapping an exciter coil around a cylindrical plasma and perturbing the confining magnetic field, $B = B_0 (1 + \delta f(t))$. The perturbations change the perpendicular energy of the particle, while leaving the magnetic moment constant. Berger et al.[1] have shown that if $f(t) = \sin \omega t$, the plasma heating rate is a second-order effect, proportional to δ^2. The magnetic moment is alternately greater and less than the unperturbed value, so the heating is a small net difference of second order. We have been able to show that if f(t) is a sawtooth function, the plasma heating rate is of first order in the parameter δ, and that its magnitude is characteristically from two to three orders of magnitude larger than that of a sinusoidal excitation. This occurs because the perpendicular energy is always above the value outside the exciter coil, and the net stochastic energy flow is unidirectional into parallel energy components.

1. J. M. Berger, et al.: Physics of Fluids, Vol. 1, No. 4, (1958) pp. 301-307.

*Supported by Air Force contract AFOSR 81-0093 (Roth)

2Q 3[9] RF Emission Power Measurement and Anomalous Drift Wave Study in a Classical Penning Discharge.* MOUNIR LAROUSSI, PAUL D. SPENCE, DAVID ROSENBERG, REZA GHAYSPOOR, and J. REECE ROTH, University of Tennessee.--We have operated a steady-state classical Penning discharge in a uniform axial magnetic field. The electron density is typically $2 \times 10^9/cm^3$ in helium gas. RF emission has been detected using broadband conical spiral and planar-spiral antennas.[1] The absolute emitted power has been measured for different plasma conditions.

A study of anomalous drift waves has been done using capacitive probes in conjunction with a Lecroy 3500-SA signal analyzer. The spectral analysis shows that two types of instabilities exist in the plasma. One exhibits a spectrum with peaks below 50 kHz[2] and a second one in the 200-300 kHz range. The high frequency waves are due to E x B motion, and the low frequency waves are due to grad ∇n type instability. The behavior of the two types of wave is different when the operating conditions change.

1. P. Spence, and J. Reece Roth, paper 3R3, IEEE International Conference on Plasma Science, St Louis, Missouri, May, 1984.
2. M. Laroussi, L. R. Baylor, P. Dehkordi, and J. Reece Roth, paper 100-4-APS Bull, Vol. 29, No.8., 1984

*Supported by Contract AFOSR 81-0093

7P5 Scaling of Radiated RF Power for Classical and Modified Penning Discharges.* DAVID ROSENBERG, PAUL D. SPENCE, MOUNIR LAROUSSI, and J. REECE ROTH, Plasma Science Laboratory, University of Tennessee, Knoxville TN 37996-2100.--Both the modified and the classical Penning discharges have been observed to emit broadband RF radiation from 50 to 1500 MHz[1]. Using a broadband calibrated antenna,[2] net integrated RF power measurements have been made of the near- and far-field radiation in the bandwidth from 100 to 1000 MHz. The RF power scaling as a function of the number density and discharge power has been measured for the two forms of Penning discharge. Near field measurements have been made in an attempt to assess some of the effects of attenuation and scattering caused by the boundary conditions of the laboratory environment. Under conditions when the far field radiation has been observed to be predominantly linearly polarized along the static B field, a dipole-like current distribution may exist in the plasma.

1. J. R. Roth, et al., Paper P1-27a, Int. Conf. on Plasma Physics, Lausanne, 1984.
2. P. D. Spence, et al., Proc. IEEE Int. Conf. on Plasma Science, (1984), p. 73, IEEE 84CH1958-8.
*Supported by AFOSR 81-0093 and ONR N00014-80-C-0063.

Plasma Heating by Collisional Magnetic Pumping*

Mounir Laroussi and J. Reece Roth

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Collisional magnetic pumping[1] is achieved by wrapping an exciter coil around a cylindrical plasma and perturbing the confining magnetic field, $B = B_0(1 + \delta f(t))$, where $f(t)$ is a bounded periodic function with a frequency below the ion cyclotron frequency. The transfer of energy between the perpendicular and parallel components of the ion velocity occurs through collisions. The change in the energy of the particles is governed by the following homogeneous linear differential equation with periodic coefficients,

$$\frac{d^2E}{dt^2} + \left[\frac{3}{2}\nu_c - \frac{d^2B}{dt^2}\left(\frac{dB}{dt}\right)^{-1}\right]\frac{dE}{dt} - \frac{\nu_c}{B}\frac{dB}{dt}E = 0$$

The above equation has been solved using Floquet's theory[2] along with a perturbation treatment. For the particular case where $f(t) = \cos \omega t$, the energy increase rate calculated[3] agrees with the one found by Berger et al.[4] The general case where $f(t)$ is an arbitrary periodic function has been treated and a condition for a heating rate proportional to the first order of the field modulation $\delta = \Delta B/B_0$ is obtained. In this case we have

$$\frac{dE}{dt} = \delta\lambda_1 E_0$$

where

$$\lambda_1 = \frac{\nu_c}{T}\int_0^T e^{\frac{3}{2}\nu_c s}\left\{\frac{1}{1-\mathrm{Exp}\left(-\frac{3}{2}\nu_c T\right)}\int_0^T e^{-\frac{3}{2}\nu_c u} f'(u)\,du - \int_0^s e^{-\frac{3}{2}\nu_c u} f'(u)\,du\right\} ds$$

First order heating is possible because of the nonlinear relationship between the magnetic field and the energy increase rate. With a perturbation that keeps the magnetic moment under the exciter coil always larger than the background value, the net stochastic energy flow is unidirectional into parallel energy components.

1. K. Miyamoto, "Plasma Physics for Nuclear Fusion", MIT Press, Cambridge, MA (1980).
2. G. Floquet, "Sur les Equations Differentielles Linearies", Annales E.N.S., T.12 (1883).
3. M. Laroussi, "Plasma Heating by Collisional Magnetic Pumping". Presented at the 18th Southeastern Symposium on System Theory, April 7-8, 1986.
4. J. M. Berger, W. A. Newcomb, J. M. Dawson, E. A. Frieman, R. M. Kulsrud, and A. Lenard, Physics of Fluids, Vol. 1, No. 4 (1958) pp. 301-307.

*Supported by AFOSR contract 81-0093 (Roth)

Appendix E

ARCHIVAL PUBLICATIONS

1982 INTERNATIONAL CONFERENCE ON PLASMA PHYSICS

JUNE 9-15, 1982
GÖTEBORG/SWEDEN

PROCEEDINGS
CONTRIBUTED
PAPERS

PRINCIPAL SPONSOR: IUPAP
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A PAIRED COMPARISON OF HIGH FREQUENCY RF EMISSION FROM TWO CONFIGURATIONS OF ELECTRIC FIELD DOMINATED PLASMA

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Abstract: We report paired comparison observations of RF emission from two steady-state electric field dominated plasmas, a classical Penning discharge operating in an axially uniform magnetic field, and a modified Penning discharge operating in an axisymmetric magnetic mirror. Measurements were made at frequencies up to 70 GHz. Much RF activity was observed below 1.0 GHz.

1. Introduction

Radio Frequency (RF) emissions from plasmas can yield diagnostic information about the electron number density (from emissions at the electron plasma frequency), and the ionic species (from emissions at the ion plasma frequency); about turbulence and nonlinear mode coupling in the plasma; and about physical processes in the plasma such as rotating spokes arising from the E/B driven diocotron instability and/or low frequency MHD instabilities. Such near-field emission phenomena are best observed in steady-state electric field dominated plasmas where conventional RF spectral analysis equipment has enough time to operate (as opposed to pulsed experiments lasting less than one second), and which have a substantial energy input through axial and transverse electric fields which penetrate the plasma. Such plasmas are generated by the classical (ref. 1) and modified (ref. 2) Penning discharges. These are known to be penetrated by strong radial and axial electric fields, up to kilovolts per centimeter, to operate with high levels of electrostatic turbulence, to heat ions by an E/B drift mechanism, and to emit RF radiation in the near field over a wide range of frequencies (refs. 3-6). In this paper we report a paired comparison of RF emissions from a classical Penning discharge, (with the plasma in a uniform magnetic field), with emissions from a modified Penning discharge which is operated in a magnetic mirror.

2. The Modified Penning Discharge

The modified Penning discharge (ref. 2) is operated in a 5:1 magnetic mirror ratio configuration which is intended to simulate the high mirror ratios of magnetospheric plasmas. The plasma is approximately 10 cm in diameter at the midplane, one meter in length, and has a maximum magnetic field up to 0.4 Tesla at the mirror throat. A schematic of the modified Penning discharge is shown in Figure 1. The plasma was operated with helium and argon gas, and is

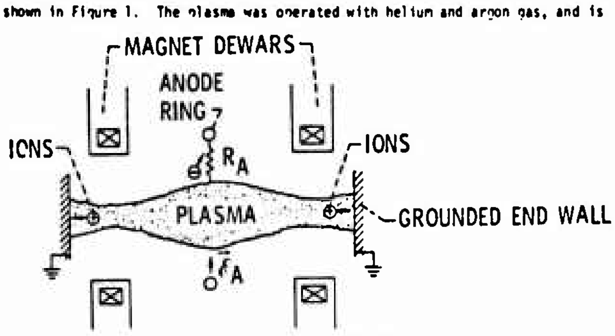

Figure 1. Schematic of the modified Penning discharge.

enclosed in a glass vacuum system which allows RF radiation to escape.

This modified Penning discharge produced two modes of RF emission, as shown in Figure 2. The low pressure mode (Mode I) shown on Fig. 2A is apparently a manifestation of the geometric mean emission frequency (Ref. 5) and harmonics out to about 500 MHz. The high pressure mode (Mode II) on Fig. 2B appears to be a manifestation of diocotron-like spokes rotating with the E/B drift velocity, with as many as 30 harmonics, sometimes visible to 500 MHz.

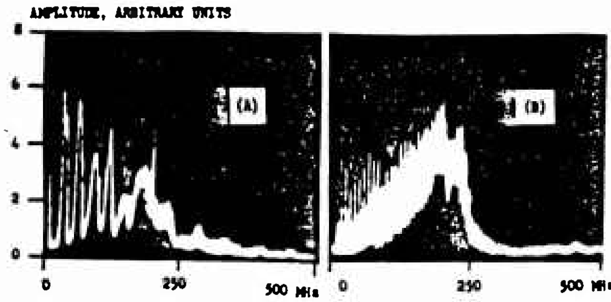

Figure 2. Spectrum of near-field emissions from the modified Penning discharge operating with helium gas at a 5:1 mirror ratio with B_{max} = 0.39 Tesla. A) Mode I operation at p_0 = 4.4 x 10^{-5} Torr, electrode voltage V_a = 4.0 kV, and electrode current I_a = 3.0 mA. B) Mode II operation at p_0 = 2.3 x 10^{-4} Torr, n_e = 7.6 x 10^9/cm^3, V_a = 2.0 kV, and I_a = 46 mA.

3. The Classical Penning Discharge

The classical Penning discharge (ref. 1) was operated with a uniform magnetic field up to 0.43 Tesla, and produced a plasma about 10 cm in diameter and one meter long. The plasma was operated in the steady state with helium and argon gas, and a glass vacuum system allowed RF radiation to escape. A preliminary spectrum of RF emission from 0 to 500 MHz is shown on Fig. 3. This plasma appears to operate in only a single mode, and to produce spectra of which Figure 3 is characteristic for both helium and argon gas. The example shown has 27 harmonics extending out to 500 MHz, and harmonics have been observed to 1.0 GHz. Many nonlinear mode coupling phenomena are apparent, including an example of plasma "lability" in which the spectral amplitude is greatest around the 8th harmonic at 200 MHz. The fundamental appears to be an example of the geometric mean emission frequency (ref. 5). RF detection equipment was used at frequencies of 10, 35, and 70 GHz, and no emissions were observed under the existing conditions.

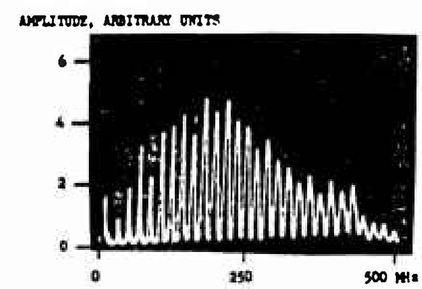

Figure 3. Spectrum of near field emissions from the classical Penning discharge with uniform magnetic field of B = 0.285 Tesla, p_0 = 2.3 x 10^{-4} Torr of argon gas, electrode voltage V_a = 2.1 kV, and electrode current I_a = 31 mA.

Acknowledgements: The classical Penning discharge investigations were supported by AFOSR contract #81-0093, and the modified Penning discharge research by ONR contract #N00014-80-C-0063

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CORRELATION OF RF EMISSION, PLASMA WAVE PROPAGATION, AND PLASMA TURBULENCE IN CLASSICAL AND MODIFIED PENNING DISCHARGES

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Abstract

We have taken data from two versions of the Penning discharge which contain highly turbulent, electric field dominated plasma with densities up to $3 \times 10^{10}/cm^3$. Auto and cross-correlation techniques were used to obtain information about the turbulence and wave propagation in this plasma from capacitive probe and microwave scattering signals.

1. Introduction

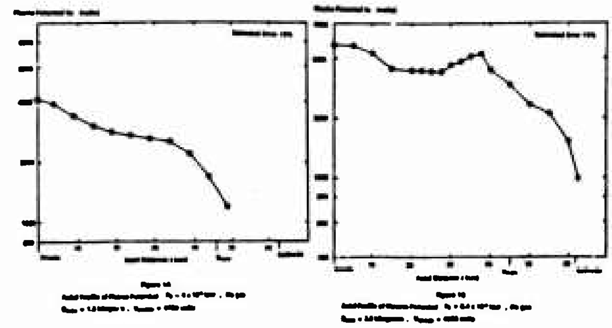
We have performed a paired comparison experiment on steady state plasma created in classical [1] and modified Penning discharges [2] in uniform and magnetic mirror geometries, respectively. Our classical Penning discharge consists of a uniform magnetic field up to 0.40 Tesla, and our modified Penning discharge of a 5.7:1 magnetic mirror ratio with a maximum magnetic field on the axis up to 0.40 Tesla. The electrons are trapped in an axial electrostatic potential well, and in both cases form a plasma about 10 cm in diameter in the midplane. The electron population forms two interpenetrating beams in the background plasma which give rise to the geometric mean and other plasma instabilities [3,4]. These plasmas support high levels of electrostatic turbulence, axial electric fields up to several hundred volts per centimeter, and emit broadband electromagnetic radiation over the frequency range from below 1 MHz to more than 2 GHz [4,5,6]. These plasmas draw anode currents up to 0.5 amps at up to 7.0 kV anode potential, and characteristically have densities that range from below $10^8/cm^3$ to above 5×10^{10}. Characteristic electron kinetic temperatures observed with Langmuir probes range from 5 to 300 eV.

Data have been taken from both discharges with an analog-to-digital data handling system which allows us to analyze the digital time series generated by electrostatic potential fluctuations detected by capacitive probes at two azimuthal or axial positions in the plasma. Auto- and cross-power spectra, the phase coherence spectrum, and dispersion relations have been observed for both plasmas. Rotating spokes, driven by E/B drift, and propagating waves have been observed and their dispersion relations obtained. These electrostatic potential fluctuations have been compared and correlated with microwave scattering results from the classical Penning discharge plasma.

RF emissions over the frequency range from 100 to 1400 MHz have been measured in the far radiation field with a spectrum analyzer connected to a specially calibrated broadband conical spiral antenna. The plasmas emit radiation with numerous harmonics of a fundamental frequency over a broad frequency range up to at least 2 GHz [4,5,6]. We have also used our antenna to make local power flux and net radiated power measurements. Axial ion energy distribution functions were measured with a retarding potential energy analyzer in both discharges, and varied from monoenergetic to Maxwellian with characteristic energies from below 100 eV to several keV. High levels of electrostatic turbulence resulted in more nearly Maxwellianized energy distributions. The modified Penning discharge seemed to produce more nearly Maxwellianized distribution functions than the classical Penning discharge, with its flat axial magnetic field profile. In both discharges, profiles of plasma potential and electron number density and kinetic temperature were taken along the axis of symmetry with a Langmuir probe under a variety of operating conditions.

2. The Modified Penning Discharge

With helium gas at pressures above 2×10^{-4} Torr, the axial profile of electrostatic potential was quite flat, with axial electric fields of only a few volts per centimeter at most. Below 10^{-4} Torr, however, electric fields up to 100 volts/cm were observed. On Fig. 1a is an example of a monotone decreasing axial potential profile for a gas pressure of 4×10^{-5} Torr of helium, $B_{max} = 0.15$ Tesla, anode voltage $V_a = 4700$ volts, a maximum number density on the midplane of $1.2 \times 10^8/cm^3$, and a characteristic $T_e = 60$ eV. On Fig. 1b is an interesting example not only of strong axial electric fields, but of an axial electrostatic potential well for ions, about 600-800 eV deep. The helium gas pressure and magnetic field were approximately twice that of Fig. 1a, $T_e = 300$ eV, and other parameters were approximately the

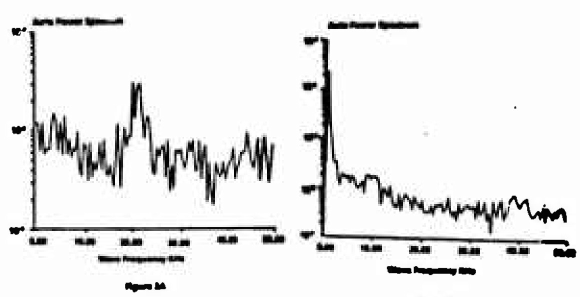


same. Both plasmas were highly turbulent, and the energy of ions escaping to the cathodes (measured with a retarding potential energy analyzer) were on the order of kilovolts. The high axial electric fields observed imply a very high anomalous resistivity for the plasma. This plasma emits multiple harmonics of a fundamental frequency which appears to be the geometric mean emission frequency associated with the interpenetrating beam plasma instability [3]. The envelope of these harmonic peaks has a maximum which is consistent with the electron plasma frequency of this discharge.

3. The Classical Penning Discharge

The classical Penning discharge also emits broadband RF radiation and under certain circumstances, the spectrum is white-noise like from 0.6 MHz to above 1.0 GHz [4]. Significant radiation has been observed above 2.0 GHz. Harmonics of the geometric mean emission frequency are observed, with a maximum envelope amplitude near the electron plasma frequency.

Measurements from a microwave scattering apparatus consisting of a 27 GHz Gunn diode in a homodyne mixer configuration were taken. Approximately 100 milliwatts of microwave power was incident on the plasma in the ordinary mode. The scattered power is observed in a plane normal to the plasma axis for scattering angles from 20° to 160°. When the scattered signal from the crystal detector is fed into a spectrum analyzer, electron number density fluctuations from 10 to 40 kHz are observed. These appear to obey a linear dispersion relation. On Figure 2a is shown an example of the spectrum of microwave scattering signals for argon gas at a



pressure of 3.5×10^{-4} Torr, at an anode voltage of $V_a = 1.8$ kV, and a magnetic field of $B = 0.25$ Tesla. On Figure 2b is an example of the auto power spectrum taken under the same operating conditions from a capacitive probe about 3 cm outside the plasma boundary. This shows no peak in the range from 10 kHz to 50 kHz.

Acknowledgements

The classical Penning discharge investigations were supported by AFOSR contract #81-0093, and the modified Penning discharge research by ONR contract #N00014-80-C-0063.

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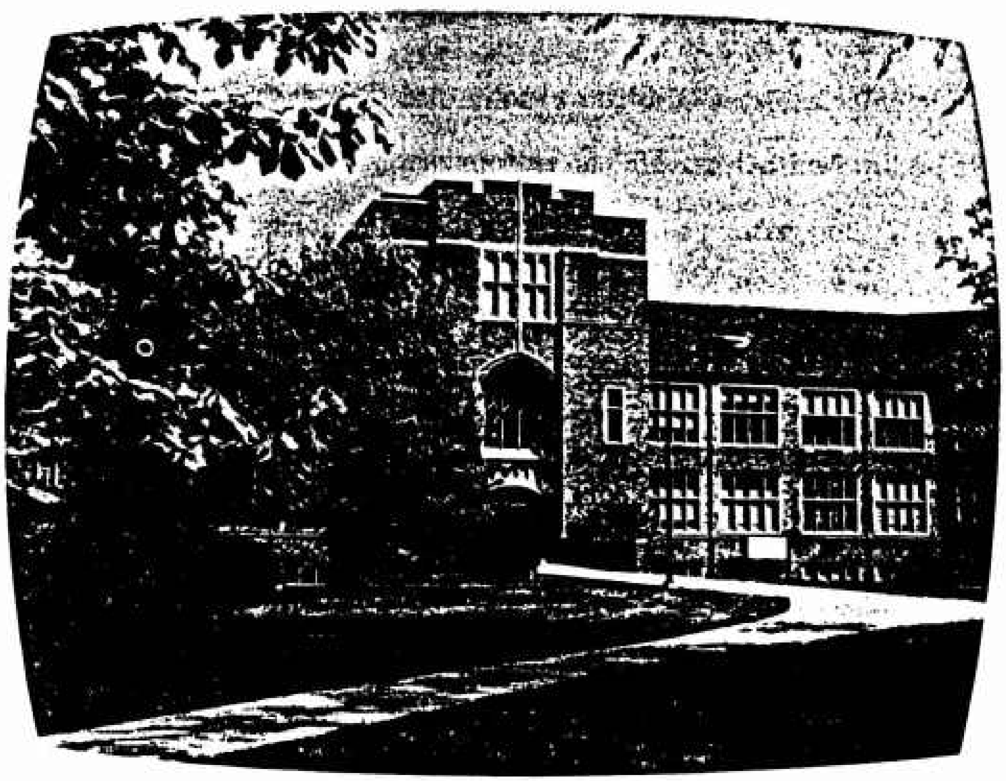

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PLASMA HEATING BY COLLISIONAL MAGNETIC PUMPING

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ABSTRACT

In controlled fusion research, it is necessary to heat plasma to kinetic temperatures of at least 10 Kev. Collisional magnetic pumping[1-3] is a potentially effective heating method which has not received much attention to date. In this paper, Floquet theory is used to solve the second order differential equation which describes the plasma heating process. The classical result with a heating rate of second order in the magnetic perturbation is obtained. Another form of magnetic perturbation is then assumed, in which first order heating is possible. A heating rate several hundred times larger than the classical one can thus be achieved.

INTRODUCTION

Collisional magnetic pumping is achieved by wrapping an exciter coil around a cylindrical plasma and perturbing the confining magnetic field, $B = B_o (1 + \delta f(t))$, where f(t) is a bounded periodic function with a frequency below the ion cyclotron frequency. The change in the energy of the particles is governed by an homogeneous linear differential equation of the second order with periodic coefficients. Examples of such equations are Mathieu's equation and Hill's equation, which appear in astronomical and other applications where the stability of periodic systems is at issue. The general solutions of these equations have been given by Floquet[4]. The form of the solution is given by:

$$F(t) = a_1 e^{\mu_1 t} \phi_1(t) + a_2 e^{\mu_2 t} \phi_2(t).$$

The parameters μ_1 and μ_2 are called the characteristic exponents. They are calculated from the characteristic equation associated with the differential equation. $\phi_1(t)$ and $\phi_2(t)$ are periodic functions with a period equal to that of the coefficients of the differential equation. In our application, Floquet's theory, along with a perturbation treatment, has been used to calculate the rate of energy increase of plasma contained in a periodically perturbed magnetic field. First a sinusoidal perturbation of the magnetic field has been assumed[5]. In this case, the rate of energy increase has been found to be proportional to the square of the field modulation factor defined by $\delta = \Delta B/B_0$. The parameter δ is a small number, so δ^2 is even smaller, and consequently the plasma heating rate is relatively small. A dependence on the first order of δ was sought. For that, a general perturbation f(t) has been assumed and a condition for first order dependence has been achieved by solving the differential equation using Floquet's theory and a perturbation treatment. (The case where a general form of the magnetic perturbation is assumed and a condition for first order heating is reached will be published in a later work.) As a specific application, a sawtooth perturbation function has been assumed. This results in a plasma heating rate dependent on the first power of δ. It improves the heating rate by two to three orders of magnitude. It is also to be noted that the collision frequency of the plasma is of great importance. In the plasma studied in the UTK Plasma Science Laboratory violent turbulence is present, yielding a high collision frequency which enhances the energy transfer, and the plasma heating rate.

SOLUTION TO THE SINUSOIDAL PERTURBATION

In the first section of this paper we are going to consider the case where the function f(t) is equal to cos ωt, which gives a sinusoidal perturbation . The magnetic field assumes the following form:

$$B = B_o(1 + \delta \cos \omega t) \tag{1}$$

where $\delta << 1$, so that the external oscillator provides a small perturbation on the original static magnetic field. At time t = o, the magnetic field under the coil is slightly stronger than its background value B_o, and half a period later, the magnetic field is weaker than the background value by the same amount. In order to have collisional heating, the transit time of the particles through the heating region has to be longer than the collision time, and both times should be much larger than the cyclotron period. Also the period of oscillation of the magnetic field is comparable to the collision time. These conditions can be written as follows

$$\tau_{ci} << \tau coll \sim \tau_f << \tau_{tr},$$

or

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$$\frac{V_i}{L} << v_c \sim \omega << \omega_{ci}$$

It is known that when the magnetic field is slowly varying in time and space, the magnetic moment,

$$\mu = \frac{E_\perp}{B} = \frac{m v_\perp^2}{2B}$$

is constant. In the absence of collisions, the constancy of the magnetic moment makes it possible to obtain a relationship between the time rate of change of the perpendicular component of the energy, and the time rate of change of magnetic field. Thus, we have

$$\frac{d\mu}{dt} = o = \frac{1}{B}\frac{dE_\perp}{dt} - \frac{E_\perp}{B^2}\frac{dB}{dt}, \tag{2}$$

from which we obtain

$$\frac{dE_\perp}{dt} = \frac{E_\perp}{B}\frac{dB}{dt}. \tag{3}$$

The total energy E of the ions is given by

$$E = E_{11} + E_\perp, \tag{4}$$

where E_{11} is the ion energy along the magnetic field lines, and $E_\perp$ is the ion energy perpendicular to the magnetic field lines, with two degrees of freedom. If no collisions occur, the perpendicular component of the ion energy, $E_\perp$, oscillates with the frequency ω, and no net heating occurs. If collisions do occur, however, some of the energy in the perpendicular component is transferred to the parallel component E_{11}. In kinetic equilibrium, the parallel component of the energy will be equal to one half the perpendicular component, as a result of equipartition. When the perpendicular component is driven by magnetic pumping, a periodic departure from equipartition occurs, and energy can be transferred between the parallel and perpendicular components. This may be expressed mathematically by adding a collisional term to Equation (3),

$$\frac{dE_\perp}{dt} = \frac{E_\perp}{B}\frac{dB}{dt} - v_c\left(\frac{E_\perp}{2} - E_{11}\right), \tag{5}$$

and

$$\frac{dE_{11}}{dt} = v_c\left(\frac{E_\perp}{2} - E_{11}\right), \tag{6}$$

where v_c is the collision frequency. Now summing Equations (5) and (6) and using Equation (4) one obtains:

$$\frac{dE}{dt} = \frac{E_\perp}{B}\frac{dB}{dt} \tag{7}$$

Thus, the rate of change of the total ion energy is proportional to the magnetic moment, and the time rate of change of the magnetic field. The net energy transfer can be obtained by taking the second derivative of Equation (7) and then using Equations (5) and (6) to eliminate the first derivative of the parallel and perpendicular components of the energy. Further, using Equation (7) itself to eliminate the perpendicular component of energy, we obtain:

$$\frac{d^2E}{dt^2} - \left|-\frac{3}{2}v_c + \frac{d^2B}{dt^2}\left(\frac{dB}{dt}\right)^{-1}\right|\frac{dE}{dt} \tag{8}$$

$$-\frac{v_c}{B}\frac{dB}{dt}E = 0.$$

Now if the sinusoidally varying magnetic field given by Equation (1) is assumed, Equation (8) becomes:

$$\frac{d^2E}{dt^2} - \left|-\frac{3}{2}v_c + \frac{\omega\cos\omega t}{\sin\omega t}\right|\frac{dE}{dt} \tag{9}$$

$$-\frac{\delta v_c\,\omega\sin\omega t}{1+\delta\cos\omega t}E = 0.$$

This is a differential equation for the change in energy due to collisional magnetic pumping. It is a differential equation with periodic coefficients. It can be solved by using Floquet theory along with a perturbation treatment. Since $\delta << 1$ the term $(1 + \delta\cos\omega t)^{-1}$ can be expanded in a Taylor series

$$(1+\delta\cos\omega t)^{-1} \approx 1 - \delta\cos\omega t + \ldots\ldots \tag{10}$$

Substituting (10) into (9), we obtain

$$\frac{d^2E}{dt^2} - \left|-\frac{3}{2}v_c + \frac{\omega\cos\omega t}{\sin\omega t}\right|\frac{dE}{dt} \tag{11}$$

$$+\delta v_c\,\omega\sin\omega t(1-\delta\cos\omega t)E = 0.$$

From Floquet theory, the solution to Equation (11) takes the following form.

$$E = a_1 e^{\lambda_1 t} p_1(t) + a_2 e^{\lambda_2 t} p_2(t) \tag{12}$$

$p_1(t)$ and $p_2(t)$ are periodic functions with a period $2\pi/\omega$. Using a perturbation treatment, λ_1 and λ_2 are found to be:

$$\lambda_1 = -\frac{3}{2}v_c + \delta\ell_1 + \delta^2\ell_2 + \ldots\ldots \tag{13}$$

$$\lambda_2 = \delta\ell_1 + \delta^2\ell_2 + \ldots\ldots \tag{14}$$

The solution associated with λ_1 is damped in time and dosen't contribute to the heating mechanism, and

therefore it will be dropped. The solution associated with λ_2 will represent heating, so from now on we will assume a solution $E = e^{\lambda_2 t}\, p_2(t)$. To find the rate of change of energy we solve for $p_2(t)$ and put the secular terms equal to zero. To do so, let's use a perturbation treatment. We take

$$p_2(t) = p_{20}(t) + \delta p_{21}(t) + \delta^2 p_{22}(t) + \ldots, \tag{15}$$

where p_{20} is the background value, and we set it equal to 1 for normalization purposes. Now let's solve the differential equation (11) for the first power of the parameter δ. We get

$$\frac{d^2P_{21}}{dt^2} + \left|\frac{3v_c}{2} - \operatorname{ctn}\omega t\right| \frac{dP_{21}}{dt} = \tag{16}$$

$$-\frac{3}{2}\ell_1 v_c + \ell_1 \omega \operatorname{ctn}\omega t - v_c \omega \sin \omega t$$

The homogeneous solution of Equation (16) is:

$$P_{21}(t) = C_1 e^{-\frac{3v_c}{2}t}\left\{a\cos\omega t + b\sin\omega t\right\} + C_2, \tag{17}$$

where

$$a = \frac{-\omega}{\omega^2 + \frac{9}{4}v_c^2}. \tag{18}$$

and

$$a = \frac{-\frac{3}{2}v_c}{\omega^2 + \frac{9}{4}v_c^2}. \tag{19}$$

The particular solution of Equation (16) is

$$\begin{aligned} p_{21}(t) = {} & -\ell_1 t + v_c a \sin\omega t \\ & - v_c b\cos\omega t + \ell_1 a \operatorname{ctn}\omega t \\ & + \left(\frac{-\ell_1}{\sin\omega t} - \frac{2}{3}\omega\right)\left(a\cos\omega t + b\sin\omega t\right). \end{aligned} \tag{20}$$

Now setting the secular term to zero provides us with the result

$$\ell_1 = o. \tag{21}$$

From the previous result we know that the rate of change is proportional to a higher power of δ. So we solve the differential equation for the second power of δ. We get the following differential equation,

$$\begin{aligned} \frac{d^2P_{22}}{dt^2} + \left(\frac{3}{2}v_c - \omega\operatorname{ctn}\omega t\right)\frac{dP_{22}}{dt} = {} & -\frac{3}{2}\ell_2 v_c \\ & + \ell_2 \omega \operatorname{ctn}\omega t + v_c \omega \sin\omega t \cos\omega t \\ & - v_c \omega \sin\omega t\, P_{21}(t) . \end{aligned} \tag{22}$$

As in the previous case the interesting part of the solution is the particular solution, and the important part of the particular solution is the part containing the secular term. The latter is found to be:

$$\left(\frac{3}{2}\ell_2 v_c b + a\ell_2\omega - \frac{1}{6}v_c\omega a\right)t . \tag{23}$$

Setting this term to zero we get

$$\ell_2 = \frac{v_c\omega^2}{6(\omega^2 + \frac{9}{4}v_c^2)} . \tag{24}$$

The growing part of the solution to Equation (11) can thus be written:

$$E = \ell^{\lambda_2 t}\, p_2(t) \tag{25}$$

$$= e^{\delta^2 \ell_2 t + \ldots}(E_o + \delta p_{21} + \delta^2 p_{22} + \ldots).$$

The term

$$e^{\lambda_2 t} = e^{\delta^2\ell_2 t + \ldots}$$

can be expanded to

$$e^{\lambda_2 t} = 1 + \delta^2 \ell_2 t + \ldots . \tag{26}$$

Inserting Equation (26) into Equation (25) an increase of energy in a time $2\pi/\omega$ is found to be.

$$\Delta E = \delta^2 \ell_2 \frac{2\pi}{\omega} E_o \tag{27}$$

Now inserting Equation (24) into Equation (27) we get:

$$\Delta E = \delta^2 E_o \frac{\pi}{3} \frac{v_c\omega}{\frac{9}{4}v_c^2 + \omega^2} . \tag{28}$$

Equation (28) can also be written as:

$$\frac{dE}{dt} = \frac{\delta^2}{6}\frac{v_c\omega^2}{\frac{9}{4}v_c^2 + \omega^2} E . \tag{29}$$

This result agrees well with the one found by Burger et al[5]. We define the heating time as:

$$t_H = \frac{6\left(\frac{9}{4}v_c^2 + \omega^2\right)}{\delta^2\omega^2 v_c}, \tag{30}$$

so

$$\frac{dE}{dt} = \frac{E}{t_H}. \tag{31}$$

The heating rate coefficient is defined as

$$\alpha = \frac{1}{t_H}. \tag{32}$$

Two limiting cases exist, the highly collisional case and the relatively collisionless case. When the plasma is highly collisional we have $v_c >> \omega$, and Equation (29) can be approximated by

$$\frac{dE}{dt} \approx \frac{2}{27}\frac{\delta^2\omega^2}{v_c}E. \tag{33}$$

The maximum value that the heating rate coefficient can take with respect to v_c is calculated from the following equation:

$$\frac{d\alpha}{dv_c} = 0, \tag{34}$$

and

$$\alpha_{max} = \frac{\delta^2 v_c}{12}. \tag{35}$$

The frequency at which α_{max} occurs is

$$\omega = \frac{3}{2}v_c. \tag{36}$$

If we operate at α_{max}, the inequalities we must satisfy are

$$\omega = \frac{3}{2}v_c << \omega_{ci}, \tag{37}$$

and

$$t_H = \frac{12}{\delta^2 v_c} < \frac{L}{V_i} = t_{tr}. \tag{38}$$

The second case is when the plasma is relatively collisionless. In this case we have $\omega >> v_c$, and Equation (29) can be approximated by

$$\frac{dE}{dt} = \frac{\delta^2 v_c}{6}E. \tag{39}$$

To get a feeling on how different are the rates of energy increase in the above two cases, let's consider a fusion plasma operating at the following parameters: $T_i = 1$ keV; $A = 2$; $n = 10^{19}/m^3$; $L = 0.5$ m; $B = 2.0$ T. The collision frequency in this case is $v_c \approx 313$ Hz leading to a heating rate coefficient

$$\alpha = \frac{\delta^2 v_c}{6} = 52\,\delta^2/\text{sec}. \tag{40}$$

Now if anomalous conductivity is present in the plasma, the collision frequency can be in the order of 5 MHz, leading to a maximum heating rate coefficient of

$$\alpha_{max} = \frac{\delta^2 v_c}{12} = 4.2\,10^5\,\delta^2/\text{sec},$$

so it can be seen that if anomalous collisions frequencies occur in the right range, an improvement of ~ 10^4 heating effectiveness can be made.

APPROXIMATE SOLUTION TO THE SAWTOOTH PERTURBATION

Let's now consider the following magnetic perturbation,

$$B = B_0\left(1 + \delta\frac{t}{t_1}\right) \text{ from } t = 0 \text{ to } t = t_1,$$

$$B = B_0\left(1 + \delta\left(-\frac{t}{t_L} + \frac{t_2}{t_L}\right)\right) \text{ from } t = t_1 \text{ to } t = t_2$$

$$\text{with } t_L = t_2 - t_1.$$

The wave-form is periodic with a period $T = t_2$. To satisfy the condition of adiabaticity, we have the following

$$t_{ci} << t_{coll} \approx t_2 \le t_{tr}.$$

The differential equation for the change in energy due to collisional magnetic pumping assumes the following form when $t \le t_1$,

$$\frac{d^2E}{dt^2} + \frac{3}{2}v_c\frac{dE}{dt} - v_c\frac{\delta/t_1}{1 + \delta t/t_1}E = 0. \tag{41}$$

For $\delta t/t_1 << 1$ the above equation becomes

$$\frac{d^2E}{dt^2} + \frac{3}{2}v_c\frac{dE}{dt} - v_c\frac{\delta}{t_1}E = 0. \tag{42}$$

The solution of Equation (42) is

$$E = C_1 e^{r_1 t} + C_2 e^{r_2 t},$$

with

$$r_1 = \frac{3}{4} v_c \left(-1 + \left(1 + 16/9 \frac{\delta}{v_c t_1} \right)^{\frac{1}{2}} \right),$$

$$r_2 = \frac{3}{4} v_c \left(-1 - \left(1 + 16/9 \frac{\delta}{v_c t_1} \right)^{\frac{1}{2}} \right).$$

Let's assume that $\delta / v_c t_1 \; 16/9 << 1$ so that

$$\left(1 + \frac{16}{9} \frac{\delta}{v_c t_1} \right)^{\frac{1}{2}} \approx 1 + \frac{8}{9} \frac{\delta}{v_c t_1} + \ldots$$

r_1 and r_2 are then equal to

$$r_1 = \frac{2}{3} \frac{\delta}{t_1}.$$

$$r_2 = -\frac{3}{4} v_c \left(2 + \frac{8}{9} \frac{\delta}{v_c t_1} \right),$$

with the boundary conditions

$$E(o) = E_o$$

$$\left. \frac{dE}{dt} \right|_{t=o} = \frac{\delta}{t_1} \frac{2}{3} E_o. \tag{43}$$

The solution of the differential equation is

$$E = E_o e^{2/3 \delta \frac{t}{t_1}}. \tag{44}$$

At $t = t_1$ $E = E_o e^{2/3 \delta} \sim E_o (1 + 2/3\, \delta)$. The heating rate during the ramping up part of the cycle is then:

$$\frac{dE}{dt} = \frac{2 \delta E_o}{3 t_1}. \tag{45}$$

For the ramping-down part of the cycle, the differential equation for the first power of δ is

$$\frac{d^2E}{dt^2} + \frac{3}{2} v_c \frac{dE}{dt} + \delta \frac{v_c}{t_L} E = o. \tag{46}$$

The boundary conditions are

$$E(t_1) = E_o (1 + \frac{2}{3} \delta), \tag{47}$$

$$\left. \frac{dE}{dt} \right|_{t=t_1} = \frac{E_1}{B} \left. \frac{dB}{dt} \right|_{t=t_1} \approx \frac{2}{3} E(t_1) \left(- \frac{\delta}{t_L} \right).$$

The second boundary condition assumes that enough collisions occur leading to equipartition. The solution to Equation (46) is:

$$E(t) = C_1 e^{-\frac{2}{3} \frac{\delta}{t_L}} + C_2 e^{-\frac{3}{2} v_c t} e^{\frac{2}{3} \frac{\delta}{t_L} t}. \tag{48}$$

As is seen from the form of E(t), it is damped in time and the contribution tc heating is small. The heating rate is basically equal to

$$\frac{dE}{dt} \sim \frac{2 \delta E_o}{3 t_1}.$$

Note that $1/t_1$ is approximately the pumping frequency so

$$\frac{dE}{dt} \sim K \delta \omega E_o, \tag{49}$$

K is a constant.

The above treatment shows that a heating rate proportional to the first power of δ is possible to achieve. A more in depth approach will be given in later work, where a condition to get first order heating is found.

CONCLUSION

Collisional magnetic pumping can be a very effective way to heat plasmas. For plasma with a high level of turbulence like the one studied in the UTK Plasma Laboratory, the collision frequency can be several MHz, leading to an enhanced heating rate due to collisional magnetic pumping. The classical heating rate that has been derived for a sinusoidal magnetic perturbation is proportional to the square of the modulation of the field δ. We have shown that with another form of perturbation a heating rate proportional to the first power of δ can be achieved. Since δ is a small number, the first order heating rate can be several hundred times larger than the classical one.

ACKNOWLEDGEMENT

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Appendix F

ABSTRACTS OF COMPLETED THESES SUPPORTED
BY AFOSR 81-0093

MICROWAVE SCATTERING AS A PLASMA DIAGNOSTIC IN A PENNING DISCHARGE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Larry R. Baylor

June 1984

ABSTRACT

A microwave scattering apparatus consisting of 32.175-GHz Gunn diode in a conventional homodyne mixer configuation has been built to investigate plasma turbulence in a steady-state classical Penning discharge. The microwaves are incident on the plasma in the ordinary mode at a power level of 25 mW. The scattered microwave power is observed for scattering angles from 20 to 160° in a plane normal to the magnetic field axis. The scattered microwaves are fed to a balanced mixer where they are detected with crystal detectors. The detected signal is then displayed on a spectrum analyzer or fed into an analog-to-digital data handling system for analysis and correlation with other signals.

In these experiments the electron number densities ranged from 10^8 to $10^{10}/cm^3$, the magnetic field ranged from 0.1 to 0.4 T, the discharge current ranged up to 0.2 A, and the input power ranged from 50 to 400 W. The frequency spectrum, angular dependence, and scattering amplitudes were measured with the microwave scattering diagnostic. Data from the microwave scattering diagnostic were correlated with plasma operating conditions and with data from capacitive probes which measured electrostatic turbulence. The data indicate strong, low-frequency electrostatic turbulence in the plasma, caused by $E \times B$ drift.

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INTRODUCTION

The scattering of microwave radiation from plasmas is a diagnostic that permits the study of electron density fluctuations in the plasma. The frequency spectrum of the scattered wave can give information about the frequency and wave number of collective electron number density fluctuations. To detect the correlated motion of the electrons, the wavelength of the incident wave must be large compared with the electron Debye distance. The amount of power scattered from thermal fluctuations in laboratory plasmas is small, therefore microwave scattering experiments are confined to the study of plasma fluctuations resulting from instabilities or driven waves.

The plasma in The University of Tennessee (UT) Plasma Science Laboratory's classical Penning discharge experiment is known to have a high level of turbulence and an electron number density in the range of 1×10^8 to $1 \times 10^{10}/\text{cm}^3$ and therefore lends itself to coherent scattering of 32-GHz microwaves. The turbulence in the plasma is believed to be primarily due to strong radial and axial electric fields and to beam-plasma interaction brought on by two interpenetrating beams resulting from electrons trapped in an electrostatic potential well.[1] The purpose of this thesis research was to develop a microwave scattering diagnostic and use it to determine additional information about the turbulence in the classical Penning discharge plasma.

COMPUTER-AIDED REDUCTION OF PLASMA DATA

A Thesis

Presented for the

Master of Engineering

Degree

The University of Tennessee, Knoxville

Saeid Shariati

March 1985

ABSTRACT

Poor signal-to-noise ratios and the nonlinear characteristics of the data obtained by most plasma diagnostic equipment makes computer-aided data handling a desirable feature in plasma laboratories. The Lecroy 3500-SA32 signal analyzer is used as the data handling system in this work. The performance of the Lecroy 3500-SA32 signal analyzer, used for recording and reducing plasma data under the noisy environment of the laboratory, is reported. The data characteristics and software programs are discussed for three types of plasma diagnostic equipment: (1) Langmuir Probes; (2) Charge Exchange Neutral Energy Analyzers; (3) Retarding Potential Energy Analyzers. Three computer programs in FORTRAN 80 are included which obtain an iterated best fit of experimental data to the corresponding analytical expressions for each case. Plasma parameters such as ion kinetic temperature, electron kinetic temperature, electron number density, plasma potential, etc. are available on a real-time basis.

TABLE OF CONTENTS

INTRODUCTION

There is a growing need for more systematic data handling in plasma laboratories. Poor signal-to-noise ratios and the nonlinear characteristics of the data obtained by most plasma diagnostic equipment makes data handling and reduction without a computer slow, subjective, manpower intensive, and (usually) unavailable on a real-time basis. By using properly programmed computers, significantly more and more precise information may be obtained about the plasma than is possible with conventional methods of data handling.

The UTK Plasma Science Laboratory is equipped with two types of plasma diagnostic equipment which can benefit from computer-assisted data reduction: (1) Langmuir probes; and (2) retarding potential energy analyzers. Computer-based data reduction techniques are applied to data generated by these diagnostic instruments. A new data acquisition and handling system will enable the user to do a real-time analysis of data by using the interactive features of the Lecroy 3500 system (Appendix C).

Three computer programs in FORTRAN 80 are included which obtain an iterated best fit of experimental data based on the least squares method for three types of diagnostic instruments: (1) Langmuir probes; (2) retarding potential energy analyzers (computer program was originally written by Loretta R. Ellis); and (3) charge exchange neutral energy analyzers. The third program, written for the charge exchange neutral energy analyzer, uses a set of pseudo data, and will

not be used in the UTK Plasma Science Laboratory for the purpose of real-time analysis of plasma data in the immediate future. These computer programs can be run on the Lecroy 3500 computer (Appendix A).

The analog data from Langmuir probes and/or retarding potential analyzers are fed into a signal conditioning system (to make the curves as smooth as possible) and digitized by a Lecroy TK8837 transient recorder (Appendix C). The digitized data are stored in the histogram memory of the Lecroy 3500 system, which can be read by the corresponding computer program on a real-time basis or can be stored on a floppy disk for later use. An isolation transformer, ISAFIL (Appendix C) is used to protect the computer internal circuitry against power line noise.

Appendix G

TITLE PAGES AND ABSTRACTS OF ITERM
SCIENTIFIC REPORTS FOR AFOSR 81-0093

Interim Scientific Report

Interim Report on Contract AFOSR 81-0093 for the Period

March 15, 1981 to June 30, 1982

Submitted to

THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

by

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for

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UTK Plasma Science Laboratory
Report No. 82-2

July 20, 1982

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PLASMA TURBULENCE, PLASMA PHYSICS, PLASMA SCIENCE, HIGH TEMPERATURE PLASMAS, RF PLASMA EMISSIONS, PLASMA HEATING, ELECTRIC FIELDS, ELECTRIC FIELD DOMINATED PLASMAS, MAGNETOELECTRIC CONFINEMENT, RF SOURCES, RF EMITTERS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This interim report summarizes accomplishments supported by AFOSR Contract No. 81-0093 during the period March 15, 1981 to June 30, 1982. During this initial phase of the contract, an electric field dominated plasma facility was designed, assembled, and put into operation. It consists of a steady state Penning discharge operating in a water-cooled magnet system which is capable of up to 0.4 Tesla. The high voltage power supply, magnet system, cooling water, and vacuum system have been assembled, and the first plasma was achieved.

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Diagnostic systems which have been put into operation thus far include spectrum analyzers to examine RF emissions to 28 GHz and a retarding potential energy analyzer. The plasma has operated for hours at a time, has exhibited a broad-band RF white-noise spectrum over frequencies from 0.5 MHz to 1.0 GHz; has produced ions with characteristic energies along the field lines of several hundred electron volts; and has exhibited evidence of strong parallel electric fields in the plasma. This plasma promises to be a rich source of information and data on physical processes in electric field dominated plasmas.

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ABSTRACT

This interim report summarizes accomplishments supported by AFOSR Contract No. 81-0093 during the period March 15, 1981 to June 30, 1982. During this initial phase of the contract, an electric field dominated plasma facility was put into operation. It consists of a steady-state Penning discharge operating in a water-cooled magnet system which is capable of 0.4 Tesla. The high voltage power supply, magnet system, cooling water, and vacuum system have been assembled, and the first plasma was achieved. Diagnostic systems which have been put into operation thus far included spectrum analyzers to examine RF emissions from 0.5 MHz to 28 GHz, and a retarding potential energy analyzer. The plasma is capable of operating for hours at a time; has exhibited a broad-band RF white-noise spectrum over frequencies from 0.5 MHz to 1.0 GHz; has produced ions with characteristic energies along the field lines of several hundred electron volts; and has exhibited evidence of strong parallel electric fields in the plasma. This plasma promises to be a rich source of information on physical processes in electric field dominated plasmas.

INTERIM SCIENTIFIC REPORT

ON

Contract AFOSR 81-0093

March 15, 1982 to March 15, 1983

J. Reece Roth

Principal Investigator

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This interim report summarizes accomplishments supported by AFOSR contract No. 81-0093 during the period from March 15, 1982 to March 15, 1983. During this second year of the contract, preliminary investigations were conducted on an electric field dominated plasma generated ina steady state classical Penning discharge operating in a water cooled magnet system capable of 0.4 tesla. Additional diagnostic systems which have been placed into service during this contract period include a high voltage Langmuir probing system for axial

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profile measurements, and an active RF diagnostic system to measure plasma number density by observing the absorbtion of RF power at the electron plasma frequency. Phenomena investigated during this contract period include RF emissions, which have been observed at frequencies from 0.5 megahertz to 2.0 gigahertz; ion energies and ion energy distribution functions: axial electrostatic potential profiles; and a rich variety of non-linear mode coupling phenomena among the various RF emissions of the plasma. The plasma is capable of operating for hours at a time under conditions which allow ready investigation of physical processes responsible for RF emissions and ion heating. This plasma is potentially a test bed to study physical processes which may also occur in weapons-related intense microwave radiation and particle beam sources which are pulsed ontime scales too short to allow ready investigation of their physics.

Report PSL 83-1

Interim Scientific Report

Interim Report on Contract AFOSR 81-0093 for the Period

March 15, 1982 to March 15, 1983

Submitted to

THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

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ON

Contract AFOSR 81-0093

March 15, 1983 to March 15, 1984

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Principal Investigator

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This interim report summarizes accomplishments support by AFOSR contract No. 81-0093 during the period from March 15, 1983 to March 15, 1984. During this third year of the contract, preliminary investigations were conducted on an electric field dominated plasma generated in a steady state classical Penning discharge operating in a water cooled magnet system capable of 0.4 tesla. Additional diagnostic systems which have been placed into service during this contract period include specially made, broadband antennae for

the measurement of absolute RF emission levels over frequencies from appr mately 50 MHz to 1200 MHz; a 32 GHz microwave scattering apparatus for th detection of plasma density fluctuations; and a 2 channel, analog-to-digi data handling system which is capable of measuring fluctuating phenomena to 10 MHz, with associated software capable of obtaining auto-and cross p spectra, phase spectra, and coherency spectra at frequencies up to 10 MHz This 2-channel data handling system was used to compare the density fluct tion signals obtained from the microwave scattering experiment with the fluctuating electrostatic potentials from a Langmuir probe; and also used compare the fluctuating electrostatic signals from two capacitive probes cated at different azimuthal or axial positions with respect to the plasm We continue to observe very broadband RF emission from the plasma under ce conditions, with white noise spectra from below a few megahertz, to frequencies as high as 2 GHz. The plasma fluctuation measurements made with microwave scattering apparatus and the capacitive probes indicate a low-frequency disturbance in the plasma in the range of 10 to 50 kHz, the frequency of which appears directly proportional to the magnetic field stren This frequency is far too low to be associated with the ion or electron cylotron frequency of the plasma, or the Alfven velocity inthis plasma. origin of this fluctuation remains a matter for continued investigation.

The plasma is capable of operating for hours at a time under conditions wl allow ready investigation of physical processes responsible for RF emissic and ion heating. This plasma is potentially a test bed to study physical processes which may also occur in weapons-related intense microwave radia and particle beam sources which are pulsed on time scales too short to al ready investigation of their physics.

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Interim Scientific Report

Interim Report on Contract AFOSR 81-0093 for the Period

March 15, 1983 to March 15, 1984

Submitted to

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UTK Plasma Science Laboratory
Report No. 84-1

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

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frequency of the plasma, or the Alfven velocity in this plasma. The origin of this fluctuation remains a matter for continued investigation.

The plasma is capable of operating for hours at a time under conditions which allow ready investigation of physical processes responsible for RF emissions and ion heating. This plasma is potentially a test bed to study physical processes which may also occur in weapons-related intense microwave radiation and particle beam sources which are pulsed on time scales too short to allow ready investigation of their physics.

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16. SUPPLEMENTARY NOTATION This report contains an account of activities on AFOSR Contract 81-0093 for the year 3/15/84 to 3/14/85.

17. COSATI CODES

FIELD	GROUP	SUB. GR.
20	09	—
17	09	—

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) Plasma Turbulence, Plasma Physics, High Temperature Plasma, RF Plasma Emissions, Electric Field Dominated Plasma, RF sources RF Emitters, Penning Discharge, Two Beam Instabilities, Transit time Magnetic Pumping, Collisional Magnetic Pumping.

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This annual progress report describes work done under AFOSR Contract 81-0093 during the period from March 15, 1984 to March 14, 1985. The experimental program accomplished extensive measurements of RF emissions from the classical Penning discharge which is operated in the UTK Plasma Science Laboratory. RF emissions were observed over a wide frequency range, from a few megahertz to more than 1 gigahertz. These emissions appear to be incoherent; the emitted radiation intensity is approximately proportional to the electron number density. An important accomplishment underlying these RF emission measurements was the development a calibrated, broadband antenna with an approximately flat frequency response, which allowed us to observe RF emissions from approximately 100 megahertz to 1.2 gigahertz.

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22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
Dr. Robert J. Barker	(202) 767-5011	AFOSR/NP

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SECURITY CLASSIFICATION OF THIS PAGE

Block #19.

During this period, microwave scattering measurements were also made by Mr. Larry Baylor on the classical Penning discharge. These revealed very high levels of number density fluctuations within the plasma, with the fluctuations reaching 6% ofthe RMS number density. An important density fluctuation phenomenon revealed during these measu ments was a spoke, which rotated about the axis ofthe discharge with a frequency of several 10's of kilohertz.

The theoretical program associated with this contract also made progress during the past year. The theory of interpenetrating electron beams, which describes the geometric mean emission frequency and is related to the high levels of electrostatic turbulence in the plasma, was extended by Professor Igor Alexeff of UTK and myself to include a cold background plasma in the region in which the two interpenetrating beams interact. A second line of theoretical investigation was initiated during this contract period by Mr. Mounir Laroussi, the Senior Research Assistant supported by this contract. He has replicated and extended some old work on collisional and transit time magnetic pumping. Some recent insights about this heating method suggest that it might be made far more efficient and effective than the old theory suggested, and we are now looking into this possibility at a theoretical level.

This contract also supported numerous other activities in aid of our experimental and theoretical research program. A major initiative of this past year was a collaborative arrangement in computational physics with Dr. Robert L. Barker of AFOSR. Our contract was used as a vehicle to enable Dr. Barker to purchase the computer hardware and software which he requires to engage in this collaborative activity. Another activity was the purchase of equipment, including a low frequency and a high frequency microwave network analyzer, with $233,745 of Fiscal year 1985 funds which UTK was given under Department of Defense-University Research Instrumentation Program. Another activity was attendance by the Principal Investigator at the International Conference on Plasma Physics in Lausanne, Switzerland during late June and early July, 1984. A paper describing research done under this AFOSR contract was presented at that meeting. The resources of the UTK Electrical Engineering Department were taken advantage of for continued software development for our Langmuir probe and retarding potential energy analyzer systems.

TABLE OF CONTENTS

SUMMARY

This annual progress report describes work done under AFOSR Contract 81-0093 during the period from March 15, 1984 to March 14, 1985. The experimental program accomplished extensive measurements of RF emissions from the classical Penning discharge which is operated in the UTK Plasma Science Laboratory. RF emissions were observed over a wide frequency range, from a few megahertz to more than 1 gigahertz. These emissions have a harmonic structure, the fundamental frequency of which appears to be associated with the geometric mean emission frequency, and the envelope of which reaches a maximum in the vicinity of the electron plasma frequency. The RF emissions appear to be incoherent; the emitted radiation intensity is approximately proportional to the electron number density, rather than to n^2. An important accomplishment underlying these RF emission measurements was the development of a calibrated, broadband antenna with an approximately flat frequency response, which allowed us to observe RF emissions from approximately 100 megahertz to 1.2 gigahertz. With these calibrated antennae, the nature of the RF plasma emissions was clearly revealed, without the complicating factor of the antenna frequency response pattern.

During this period, microwave scattering measurements were made by Mr. Larry Baylor on the classical Penning discharge. These revealed very high levels of number density fluctuations within the plasma, with the fluctuations reaching levels of 6% of the RMS number density. This very violent plasma turbulence is characteristic of the electric field dominated plasmas found in Penning discharges. An important density fluctuation

phenomenon revealed during these measurements was a spoke, which rotated about the axis of the discharge with a frequency of several 10's of kilohertz. These density fluctuations appeared in phase along the magnetic field lines, and rotated as an m = 1 mode about the discharge axis. During the latter part of the period covered by this report, preparations were made to take absolute measurements of the RF emission power from the plasma.

The theoretical program associated with this contract also made progress during the past year. The theory of interpenetrating electron beams, which decribes the geometric mean emission frequency and is related to the high levels of electrostatic turbulence in the plasma, was extended by Professor Igor Alexeff of UTK and myself to include a cold background plasma in the region in which the two interpenetrating beams interact. These theoretical developments have made it possible to explain RF emission at frequencies between the geometric mean emission frequency (appropriate for no cold background plasma in the interaction region) and emission at the electron plasma frequency, appropriate when the interacting electron beam densities are much smaller than the cold background plasma density in the interaction region. This theoretical work was written up by Professor Alexeff and the Principal Investigator, and reported at the APS Plasma Physics Division meeting in October, 1984.

A second line of theoretical investigation was initiated during this contract period by Mr. Mounir Laroussi, the Senior Research Assistant supported by the contract. He has replicated and extended some old work on collisional and transit time magnetic pumping, a plasma heating scheme which was put forward in the 1950's during the early days of fusion research,

but which was not followed up after about 1960. Some recent insights about this heating method suggest that it might be made far more efficient and effective than the old theory suggested, and we are now looking into this possibility at a theoretical level. If the theory appears promising, we may propose, in an extension of our current contract, to look at this phenomenon experimentally.

This contract also supported numerous other activities in aid of our experimental and theoretical research program. A major initiative of this past year was a collaborative arrangement in computational physics with Dr. Robert L. Barker of AFOSR. This contract was used as a vehicle to enable Dr. Barker to purchase the computer hardware and software which he requires to engage in this collaborative activity. Another activity was the purchase of new equipment, including a low frequency and a high frequency microwave network analyzer, with $233,745 of fiscal year 1985 funds which UTK was given under the Department of Defense-University Research Instrumentation Program. The funds were not available until early February, 1985, but the necessary shopping and bargaining among vendors required much of our time from September, 1984, until the orders were placed in February, 1985. This equipment has begun to arrive at the present writing, and we anticipate major advances in our experimental research program as a result of the availability of this state-of-the-art equipment. The contract for the Research Instrumentation Program Grant is included as Appendix D.

Another activity was attendance by the Principal Investigator at the International Conference on Plasma Physics in Lausanne, Switzerland during late June and early July, 1984. A paper describing resarch done under this

AFOSR contract was presented at that meeting, and the Principal Investigator took the opportunity to visit three major European plasma physics laboratories, a trip report on which is included as Appendix C of this report. The resources of the UTK Electrical Engineering Department were taken advantage of for continued software development of our Langmuir probe and retarding potential energy analyzer system. We have also taken advantage of the DoD Surplus Property Disposal System to obtain, from 3 screening trips, useful microwave and electronic test equipment which greatly extend our ability to do exploratory research.

Appendix H

PLASMA SEMINARS, 1982-86

5990 EE - PHYSICS PLASMA SEMINAR

Winter Quarter, 1982

Room 405 Ferris Hall
12:00 noon, Fridays

We have asked several outside speakers to come and describe their recent plasma-related work to us. The dates, speakers and approximate topics are as follows:

February 12 - Dr. Owen Eldridge, Fusion Energy Division, ORNL - Current Status of Ion Cyclotron Resonance Heating and recent results from the ORNL EBT-S Experiment.

February 19 - George E. Gorker, Fusion Engineering Design Center, ORNL - Engineering Problems Associated with Handling Large Blocks of Electrical Power for Present and Future Magnetic Fusion Experiments.

February 26 - Philip T. Spampinato, Fusion Engineering Design Center, ORNL - Reference Design and Current Status of the Fusion Engineering Device (FED).

March 5 - Philip Ryan, Fusion Energy Division, ORNL - Status report on his Ph.D. thesis in EE, on the subject of neutral beam development for plasma heating.

Students, faculty and staff are welcome to attend.

5990 EE - PHYSICS PLASMA SEMINAR

Spring Quarter, 1982

Room 405 Ferris Hall
12:00 noon, Fridays

We have asked several outside speakers to come and describe their recent plasma-related work to us. The dates, speakers and approximate topics are as follows:

April 16 -- J. Rand McNally, Jr., Fusion Energy Division, ORNL (retired)
The physics of advanced fuel fusion.

May 7 -- Prof. Edward G. Harris, Department of Physics, UTK
Catastrophe theory as applied to the ELMO Bumpy Torus and other plasmas.

May 28 -- Dr. Vishnu Srivastava, Fusion Engineering Design Center, ORNL. Superconducting magnet technology in the Fusion Engineering Device (FED).

Students, faculty, and staff are welcome to attend.

PH 5990

Plasma Seminar Schedule Fall 1983

Room 504 Ferris Hall
12:00 Noon, Wednesdays

DATE	SPEAKER AND TOPIC
Sept. 28 -	Prof. Igor Alexeff - Beam-Plasma Instabilities
Oct. 5 -	Mr. Paul Spence - Broadband Antennas
Oct. 12 -	Prof. J. Reece Roth - Scaling Laws for Fusion Reactors
Oct. 14 -	Prof. D Rosenberg - Network Analyzers
Oct. 26 -	Prof. Igor Alexeff - Recent Results in Orbitron Research
Nov. 2 -	Dress Rehearsals for the APS Plasma Physics Divison Meeting
Nov. 9 -	No Plasma Seminar
Nov. 16 -	Trip Report on APS Plasma Physics Division Meeting
Nov. 23 -	Dr. Owen Eldridge, ORNL - Electron Cyclotron Plasma Heating
Nov. 30 -	Mr. Peyman Dehkordi - Operation of the Analog-to-Digital Data Handling System.

All interested persons are invited to attend.

For further information contact

Prof. J. Reece Roth
Dept. of Electrical Engineering
(615) 974-4446

UTK PLASMA SCIENCE SEMINAR SERIES

FALL, 1984

Wednesdays, 9:00 AM 504 Ferris Hall

DATE	
September 26	Profs. Alexeff and Roth, Trip Report on the International Conference on Plasma Physics, Lausanne, Switzerland
October 3	Prof. I. Alexeff, "Recent Progress with the Orbitron Maser"
October 10	Ms. Lisa Hood and Mr. John Clark, UTK Office Of public Relations, "How to Deal with Reporters"
October 17	Prof. J. R. Roth, "Recent Progress with Two Beam Interaction Instabilities"
October 24	Dress Rehearsals for the APS Plasma Physics Division Annual Meeting
October 31	NO SEMINAR - APS MEETING WEEK
November 7	Prof. J. R. Roth, "Plasma Etching for Microelectronics", based on materials provided by J. W. Coburn, IBM
November 14	Mr. William Casson, ORNL, "Far Infrared Scattering on EBT"
November 21	Mr. Phillip Spampinato, Fusion Engineering Design Center, ORNL "Robotics in Fusion Research"
November 28	Prof. J. R. Roth, "How to Get Government Research Contracts"
December 5	Topic to be arranged.

WINTER QUARTER 1985

PLASMA SCIENCE SEMINAR SERIES

Room 504 Ferris Hall
Tuesdays, 9:00-10:15 am

DATE	SPEAKER AND TOPIC
January 15	J. Reece Roth, "How to Obtain Surplus Government Equipment for Experimental Research"
January 24 THURSDAY	Dr. Robert J. Barker, AFOSR, Bolling AFB, Washington, D.C., "Two-and Three-Dimensional Particle-in-Cell Electromagnetic Plasma Simulation".
January 29	Prof. Igor Alexeff, "Recent Results in Orbitron Research"
February 5	Prof. J. Reece Roth, "Plasma Etching fo Microelectronics-II", Based on notes and vue-graphs supplied by J. W. Coburn of IBM.
February 12	Prof. David Rosenberg and Mr. Paul D. Spence, "RF Plasma Emissions Measured with Calibrated, Broadband Antenna".
February 19	Mr. Antonino Carnevali, Fusion Energy Division, ORNL,"Confinement of Beam Ions in the ISX-B Plasma". This willl be a report on Mr. Carnevali's Ph.D. thesis in the Physics Department.
February 26	Dr. Michael J. Gouge, DoE Program Office, Oak Ridge, "Alpha-Driven Currents in Tokamak Reactors". Dr. Gouge will present his recently-completed Ph.D. thesis for the UTK Physics Department.
March 5	Mr. Wlodzimierz (Vlodek) Nakonieczny, "Particle Orbits in the Orbitron Microwave Emitter". This will be a progress report on a Ph.D. Thesis.
March 12	Mr. Mounir Laroussi, "Progress in Theoretical Understanding of Transit-Time Magnetic Pumping and Collisional Plasma Heating".

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

For further information, contact J. Reece Roth, 974-4446

SPRING QUARTER 1985

PLASMA SCIENCE SEMINAR SERIES

Room 504 Ferris Hall
Thursdays, 9:00-10:15 am

DATE	SPEAKER AND TOPIC
April 4	Mr. Gregory Hutchens, University of Illinois, "Group Invariance Properties of the Grad-Shafranov Equation". Mr. Hutchens is a graduate of the UTK Engineering Physics program now studying at Illinois in their Nuclear Engineering Program.
April 11	Prof. Igor Alexeff, "Recent Results from the Orbitron Microwave Emitter at Submillimeter Wavelengths".
April 18	Profs. J. Reece Roth and David Rosenberg, UTK, and Dr. Howard Adler, ORNL, "Interaction of Electromagnetic Radiation with Biological Samples" Joint meeting with the Department of Microbiology and other interested persons to explore research opportunities in this area.
April 25	Mr. Paul Spence, "Measurement of RF Plasma Emissions with Calibrated Antennas", A progress report on Mr. Spence's research program in the UTK Plasma Science Laboratory.
May 2	W. Don Nelson, ORNL Fusion Engineering Design Center, "The Fusion Power Demonstration Study".
May 9	Mr. Fred Dyer, Experimental Technique Associated with Orbitron Microwave Emitters"
May 16	Mr. Mounir Laroussi, "Recent Theoretical Progress on Collisional and Transit-Time Plasma Heating", A progress report on Mr. Laroussi's Ph.D. research program.
May 23	Mr. G. Reza Ghayspoor, "Progress in the Development of a VAX-Assisted Data Handling and Reduction System for Plasma Measurements", A progress report on Mr. Ghayspoor's M.S. thesis research.
May. 30	Dress Rehearsals for poster papers at the IEEE International Conference on Plasma Science, Pittsburgh, PA, June 3-5, 1985.

FALL QUARTER 1985-1986

PLASMA SCIENCE SEMINAR SERIES

EE 5990 - - Section 34482

Room 504 Ferris Hall

Thursdays, 12:00 to 1:15 p.m.

DATE	SPEAKER AND TOPIC
October 3	Prof. Igor Alexeff, A Plasma Wave Oscillator.
October 10	Prof. J. Reece Roth, The Impact of Plasma Heating Efficiency on the Power Balance of Powerplant Fusion Reactors. This is a dress rehearsal for an invited talk and conference paper.
October 17	Paul Spence, Operation of the HP Microwave Network Analyzer, Followed by a hands-on workshop with the instrument in the UTK Plasma Science Laboratory.
October 24	G. Reza Ghayspoor, Development of an Integrated Data Acquisition and Handling System for the Measurement of Radial Transport Rates, Based on Digital Time Series Analysis. This is a M.S.E.E. thesis summary.
October 31	Dress rehearsals of papers for APS Plasma Meeting.
November 7	NO SEMINAR - APS MEETING WEEK
November 14	F. William Wiffen, Metals and Ceramics Division, and Fusion Engineering Design Center, ORNL; Materials Problems and Potential Solutions in Fusion Reactors.
November 21	David Coffey, President, The Nucleus, Inc., How to Start Your Own Small Business.
December 5	John E. Crowley, Low-Noise Measurements of Plasma Turbulence.

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

For further information, contact J. Reece Roth, 974-4446

PLASMA SCIENCE SEMINAR SERIES

EE 5990--Section 32437
Room 504 Ferris Hall
Fridays, 12:00 to 1:15 p.m.

DATE	SPEAKER AND TOPIC
January 10	Prof. Igor Alexeff, Department of Electrical Engineering UTK, "Trip Report on the Infrared and Millimeter Wave Conference". This IEEE cosponsored conference was held in December, and many new advances were reported.
January 17	Prof. Karl Audenaerde, Chairman, Engineering Department, State University of New York at New Platz,"Microwave Mode Convertors".
January 24	Prof. J. Reece Roth, Department of Electrical Engineering, UTK, "Transit Time Effects on the Divergence Term of the Plasma Continuity Equations".
January 31	Mr. John E. Crowley, GRA, UTK Plasma Science Laboratory, Low-Noise Measurements for Plasma Turbulence Research". This status report will cover Mr. Crowley's Master's thesis research in the UTK Plasma Lab.
February 7	Mr. G. Reza Ghayspoor, GRA, UTK Plasma Science Laboratory, "Extension of the LeCroy Transient Recorder System to Three Simultaneous Channels". This is an updating of Mr. Ghayspoor's recent Master's degree.
February 14	Mr. Mounir Laroussi, GRA, UTK Plasma Science Laboratory, "First-Order Plasma Heating Using Collisional Magnetic Pumping". This status report will describe the theoretical aspects of Mr. Laroussi's Ph.D. thesis.
February 21	Prof. J. Reece Roth, Department of Electrical Engineering, UTK, "How to Write a Textbook". Useful hints on writing a textbook in the word-processor era and some interesting aspects of the book publishing business will be discussed.
February 28	Prof. Marshall Pace, Department of Electrical Engineering, UTK, "Research at UTK on the Initiation of Dielectric Breakdown". Prof. Pace will describe some research underway at UTK in this area.
March 7	Prof. J. Reece Roth, Department of Electrical Engineering, UTK, "Theoretical and Experimental aspects of the Plasma Continuity Equation Oscillation". This will describe a plasma instability first discovered experimentally and described theoretically by Prof. Roth.
March 14	Dr. Robert W. Schumacher, Hughes Research Laboratories, Malibu, California, "Microwave Tube Research at the Hughes Research Laboratories". Dr. Schumacher will discuss the Hughes research program in this area, including their work on the Orbitron maser.

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

For further information, contact J. Reece Roth, 974-4446

WINTER QUARTER, 1986

PLASMA SCIENCE SEMINAR SERIES

Spring, 1986

EE 5990--Section 33236
Room 504 Ferris Hall
Fridays, 12:00 to 1:15 pm

Date	SPEAKER AND TOPIC
April 4	Organization meeting and dress rehearsals for the 1986 SSST Plasma Papers
April 11	Prof. Igor Alexeff, Department of Electrical Engineering, UTK "Recent Progress in Orbitron Research".
April 18	Mr. John B. Miller, Fusion Engineering Design Center, ORNL, "Prevention of the Current-Quench Phase of a Major Disruption in a Tokamak Reactor" This plasma engineering study is Mr. Miller's Ph.D. Thesis in Nuclear Engineering.
April 25	Mr. Tim Bigelow, Fusion Energy Division, ORNL, "A Survey of Plasma RF Heating Experiments in Japan". A report of his recent trip to Japanese Fusion Labs.
May 2	Profs. J. Reece Roth and Igor Alexeff, Dept. of Electrical Engineering, UTK. "A Study of Tokamak Confinement Time Scaling Based on MHD Current Penetration". A derivation of an alcator-like confinement time scaling from first principles.
May 9	Mr. John E. Crowley, GRA, UTK Plasma Science Laboratory, "Conversion of the HP 3577A Network Analyzer to a Low Noise Spectrum Analyzer Mode of Operation". This seminar will double as Mr. Crowley's oral exam on his M.S. Thesis.
May 16	Mr. Phil Ryan, Fusion Energy Division, ORNL, and UTK Ph.D. candidate, "Analysis and Design of an Energy Recovery System for a Space Charge Neutralized Ion Beam". A summary of Mr. Ryan's Ph.D. Thesis.
May 23	Prof. J. Reece Roth, Department of Electrical Engineering, UTK, "Trip Report on the 13th IEEE International Conference on Plasma Science, Sakatoon, Canada," and "Langevin Formalism for Absorbtion of RF Power at Gyroresonance"
May 30	Mr. Paul Spence, GRA, UTK Plasma Science Laboratory, "Measuring Collision Frequencies by Microwave Absorbtion"

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

For further information, contact J. Reece Roth, 974-4446